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STUDY OF METHODS FOR SYNCHRONIZING REMOTELY-LOCATED CLOCKS

Prepared by
SPERRY GYROSCOPE COMPANY
Great Neck, N. Y.
for Goddard Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1967

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FOREWORD

This study is made for the Timing Systems Section, Space Data Control Branch, Advanced Development Division, Goddard Space Flight Center, Greenbelt, Maryland.

The study is primarily intended for internal use; however, the report contains general information which is of interest to all who are interested in time synchronization. Additionally, this report presents the different methods for clock synchronization and is a handy reference. For this reason the report is made available for general distribution.

The accuracy of the descriptions, analyses, and numerical presentations has been checked. However, certain errors remain (such as UT-2 should all be changed to UT-C on page 7, and the UT-C off-set frequency should be -170×10^{-10} for 1958 and -150×10^{-10} for 1959 in Figure 1, etc.) and are not corrected. The readers are cautioned in quoting the content without checking its accuracy. The more recent references and bibliography are given although they are by no means complete or exhaustive. It is hoped that through these, earlier reports and publications may be obtained.

Andrew R. Chi

Andrew R. Chi, Head
Timing Systems Section

ABSTRACT

As documented in this report, the development of suitable methods for synchronizing remotely-located clocks has, in recent years, been the objective of a large number of investigators. The solutions proposed range from comparatively simple to quite complex techniques for overcoming the problems involved.

In order to reach the conclusions of this study, the report first discusses time scale functions, the characteristics of radio propagation, frequency standards, and portable clocks. The characteristics of currently available or proposed time synchronization systems in all major frequency bands are then surveyed - as well as those of line-of-sight and satellite systems. Fundamental considerations of time synchronization are reviewed in detail and the design for an OMEGA timing receiver is fully discussed.

The choice of a practical clock synchronization system - it is seen from the findings of this study - is determined by the particular requirements of three basic considerations: (1) the synchronization accuracy desired, (2) the size of the area within which synchronization is to be implemented, and (3) the relative accessibility of the remote clocks to the receipt of synchronizing data within their area.

Analysis of these three factors shows that as the accuracy requirement is increased, the cost rises proportionately due to greater system complexity, operational costs, and synchronization logistics. With the present trend towards ever-increasing area coverage and greater separation between clocks, many of the candidate synchronization systems cannot meet the new requirements and thus must be eliminated from consideration. In the area of accessibility, the problems of signal transmission through varying media also exclude the use of certain techniques.

Although this study was not conducted for the purpose of defining a specific system to meet certain requirements, it is recommended in any case that serious consideration be given to the use of a Slave clock set once by a Master clock and stabilized by reference to VLF signals. Good accuracy and relatively low cost will both be achieved in such a system.

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SECTION I

INTRODUCTION

A. GENERAL

This final study report, covering an investigation of methods for synchronizing remotely-located clocks, is submitted to the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Md., by the Information and Communications Division, Sperry Gyroscope Company Division of Sperry Rand Corporation, Great Neck, New York, in accordance with the requirements of Contract NAS-5-9905, dated 30 June 1965. The investigation was conducted over the 9-month period from July 1965 to April 1966.

B. STUDY OBJECTIVE AND SCOPE OF REPORT

This study was undertaken to provide an analysis of techniques for synchronizing remotely-located clocks. The report surveys the various methods of clock synchronization available or seriously proposed at the present time (1966). Background data are given to substantiate the analysis and to enable the reader to evaluate the various techniques that may be applicable to his own interests and requirements.

The report is organized to furnish, first, background information on time scales, electromagnetic propagation, and frequency standards; the various clock synchronization systems are then discussed in detail - including the capabilities of each system and the accuracy to be expected. Fundamental system-design information is included, where possible, to enable the reader to evaluate each system with respect to his own peculiar requirements.

A bibliography listing the sources of much of the contents of this report is included as Section XI. Additional publications, which provide further information relevant to the problem, are also given in this listing.

Appendices I and II contain, respectively, a detailed discussion of the fundamentals of time synchronization and the design details of a receiver for deriving timing signals from the OMEGA system.

SECTION II

TIME SCALE FUNCTIONS

A. GENERAL

This section assumes a basic understanding of the time synchronization process. It describes the time scales most commonly used, how and by whom they are derived and how they are disseminated. Definitions of time, time scales, and synchronization are discussed from both the abstract and concrete viewpoints in Appendix I of this report.

B. TIMEKEEPING ORGANIZATIONS

A number of organizations have responsibility for various aspects of the keeping of time. Three of these - BIH, NBS, and USNO - are of particular importance to users of precise time in the U.S. Their principal features are as follows:

- BIH, the Bureau International de l'Heure, Paris, France, is the organization responsible for international time coordination. The time and frequency of signals transmitted from all over the world are recorded by BIH, and periodic bulletins are published.
- NBS, the National Bureau of Standards Radio Standards Laboratory, maintains the U.S. Frequency Standard at Boulder, Colorado, from which it controls the time and frequency transmissions of WWV, WWVH, WWVL, and WWVB.
- USNO, the U.S. Naval Observatory, maintains the DOD Master Clock, which is the time reference for all U.S. defense organizations. USNO controls the time signals from Navy radio stations such as NSS and NBA, and the Loran-C station at Cape Fear, North Carolina. There are two observatories, one in Washington, D.C. and one in Richmond, Florida.

Other laboratories participating in time studies include:

- NRL, U.S. Naval Research Laboratory (Washington, D.C.)
- CNET, Laboratoire de CNET (Bagneux, France)
- NRC, National Research Council of Canada (Ottawa, Canada)
- RRL, Radio Research Laboratory (Tokyo, Japan)

- RIND, Research Institute of National Defense (Stockholm, Sweden)
- NPL, National Physical Laboratory (Teddington, England)
- LSRH, Laboratorie Suisse des Recherches Horlogeres (Neuchatel, Switzerland)
- RGO, Royal Greenwich Observatory (Herstmonceux, England).

C. TIME SCALES

Several time scales in current use represent different measurements relative to natural phenomena. The most common are Ephemeris Time (ET), Atomic Time (AT), and Universal Time (UT).

1. Ephemeris Time, ET

ET is the uniform time scale used to determine the position of celestial bodies. The scale is defined by the orbital motion of the earth about the sun. The second of ET is defined as 1/31, 556, 925.9747 of the tropical year for 0 January 1900. In practice, ET is obtained from the orbital motion of the moon about the earth. The computed position of the moon with respect to the stars is tabulated as a function of ET in the Improved Lunar Ephemeris. An observed position of the moon gives the ET of the epoch of observation of interpolation in the Improved Lunar Ephemeris. Since June 1952, the U.S. Naval Observatory has been determining Ephemeris Time with the dual-rate moon position camera.

2. Atomic Time, AT

In June 1955, a cesium-beam frequency standard was placed in operation at the National Physical Laboratory, Teddington, England, and a joint program with USNO was undertaken to determine the frequency of cesium in terms of the second of Ephemeris Time. The frequency obtained for zero magnetic field during the interval from June 1955 to March 1958 is

$$f_{cs} = 9\ 192\ 631\ 770 \pm 20 \text{ cycles per second (of ET)}$$

This measurement established a system of AT which is related to the second of ET. It is necessary to specify the rate at which AT increases, as well as the value of AT at some epoch, since an atomic clock does not furnish epoch. The system is defined as follows:

- A clock which keeps AT advances 1 second in the interval required for 9 192 631 770 oscillations of cesium at zero field. The uncertainty of 2 parts in 10^9 has been avoided by defining f_{cs} as being exactly equal to the foregoing number, as was officially announced[1] by the International Committee of Weights and Measures at the Twelfth General Conference held at Paris, France, in October 1964.
- At $0^h\ 0^m\ 0^s$ UT2 on 1 January 1958 a clock which indicated AT was in agreement with a clock which indicated UT2. At that time the clock operating on AT was gaining $0^s.0017$ per day on the clock on UT2, as derived from other data. This rate of gain changes as the speed of rotation of the earth varies.

A number of sources of AT are located in the U.S. and abroad. Four of these AT's, designated NBS(A), A.1, A.3, and AM, have their epoch related to the same origin, 1 January 1958.

NBS(A) is atomic time as kept by the U.S. Frequency Standard (USFS), a cesium-beam device maintained by NBS in Boulder, Colorado. The atomic second, as so defined, is transmitted by radio station WWVB.

A.1 atomic time is maintained by USNO in Washington, D.C. The timekeeping is currently accomplished by reference to a hydrogen maser at NRL, but it is compared with data from cesium-beam standards at USNO, at Boulder (USFS); NPL, Teddington, England; and from LSRH, Neuchatel, Switzerland (ref. 77A).[2]

Atomic times A.3 and AM are maintained by BIH in Paris. A.3 is derived from a concensus of inputs from NPL, LSRH, and USFS. AM is formed by the weighted average of these three sources plus those of NRL; CNET, Bagneux, France; NRC, Ottawa, Canada; USNO; RRL, Tokyo; and RIND, Stockholm. BIH publishes, in its "Bulletin Horaire," its observations of these time scales, relative to UT, approximately 6 months after the fact (ref. 23A).

3. Universal Time, UT

UT, which is a form of mean solar time, is based upon the rotation of the earth. Since the speed of rotation of the earth varies, UT is not constant. There are three kinds of UT: UT0, UT1, and UT2. They are defined as follows:

- - - - - - -

[1]The exact wording of the Conference's action was: "The standard to be employed is the transition between the two hyperfine levels F = 4, $M_F = 0$ and F = 3, and $M_F = 0$ of the fundamental state $^2S_{1/2}$ of the atom of cesium 133 undisturbed by external fields and the value 9 192 631 770 hertz is assigned." As such, the new definition replaces that based on the orbit of the earth around the sun.

[2]All bibliographical references are listed numerically in Section XI of the report.

- UT0, Universal Time (0). This is a slightly-variable time scale inferred from direct observation of the sidereal time, usually of the zenith transit of stars. (UT0 is determined from astronomical observations made at some 44 observatories around the world, with the data being collected by BIH in Paris.)
- UT1, Universal Time (1). This time scale is obtained from the scale UT0 by correcting for polar motion inferred from observations of the observatories' latitude. Each interval (nominally 1 second) on the UT1 scale corresponds to a rotation of the earth by 15 arcseconds with an accuracy of approximately 1 millisecond.
- UT2, A Smoothed Universal Scale. Since the rotation of the earth on its axis is not quite uniform, the scale UT1 is variable and includes regular seasonal fluctuations. The difference in seconds between the two scales can be expressed as

$$UT2 - UT1 = 0.022 \sin 2\pi y - 0.012 \cos 2\pi y +$$

$$-0.006 \sin 4\pi y + 0.007 \cos 4\pi y$$

where y is in years (ref. "Bulletin Horaire" (BIH), January, February, 1964). The addition of this variation to UT1 leaves the smoother-scale UT2. UT2 has short-term and long-term fluctuations (which are not, so far, predictable) ranging in amplitude from milliseconds to seconds.

4. Coordinated Universal Time UTC

In order to obtain a uniform time scale which can be used as a working standard, BIH now maintains UTC, whose rate is adjusted each year to approximate UT2. To make this approximation, BIH predicts the rate of departure of UT2 from ET (and AT) and the coordinated agencies then offset the rate of their clocks accordingly. For 1966 the offset (known as the "Universal Offset") is 300×10^{-10}. In addition, if required, BIH orders step time adjustments of 100 ms in order to keep UTC within 100 ms of UT2. In 1964 and 1965, when the offset was 150×10^{-10}, six step time adjustments were required. So far none has been required in 1966. The time divergence between UT2 and WWV is shown in figure 1 for the period starting in 1958 (origin of AT). Prior to the fall of 1964, the frequency offsets and step time adjustments were the result of observations of USNO. Since that time, BIH has had that responsibility.

D. TIME AND FREQUENCY DISSEMINATION

The Department of Defense, in Directive No. 5160.51, dated 1 February 1965, assigned to the U.S. Naval Observatory the responsibility "for establishing, coordinating, and maintaining capabilities for time and time intervals (astronomical and atomic) for use by all DOD components, DOD contractors, and related scientific laboratories." The Observatory maintains the DOD Master

Clock and has recently obtained portable atomic clocks which allow calibration or setting of remote clocks to microsecond accuracy.

The National Bureau of Standards maintains the "U. S. Frequency Standard," from which the timing and frequency of the signals from WWV, WWVH, WWVB, and WWVL are derived. The manner in which these stations are synchronized is shown in figure 2, while figure 3 gives their broadcast schedules.

In order to produce UT2, the frequencies of WWV, WWVH, and WWVL are offset from the frequency of the U. S. Time Standard by an increment equivalent to the Universal Offset (-300 parts in 10^{10} for 1966). UT2 generated by these three sources is monitored and checked against UTC by BIH in Paris. In addition, USNO monitors WWV and publishes weekly observations of the differences (to 0.1 ms) between NBS (UA) and UT2.

Station WWVB, however, transmits NBS(A) seconds since its frequency is not offset; however, the timing of the seconds is shifted periodically in steps of 200 ms so that the time of the second tick from WWVB is always within approximately ±100 milliseconds of UT2. At the present offset rate, this adjustment should be made at intervals of slightly over two months. The WWVB second pulse was retarded 200 ms on 1 March and 1 June 1966. Along with the 1-second marks, WWVB also transmits a binary code (figure 4) which gives the time of an index to the nearest minute and also gives the correction between the 1-second marks and UT2 to the nearest millisecond.

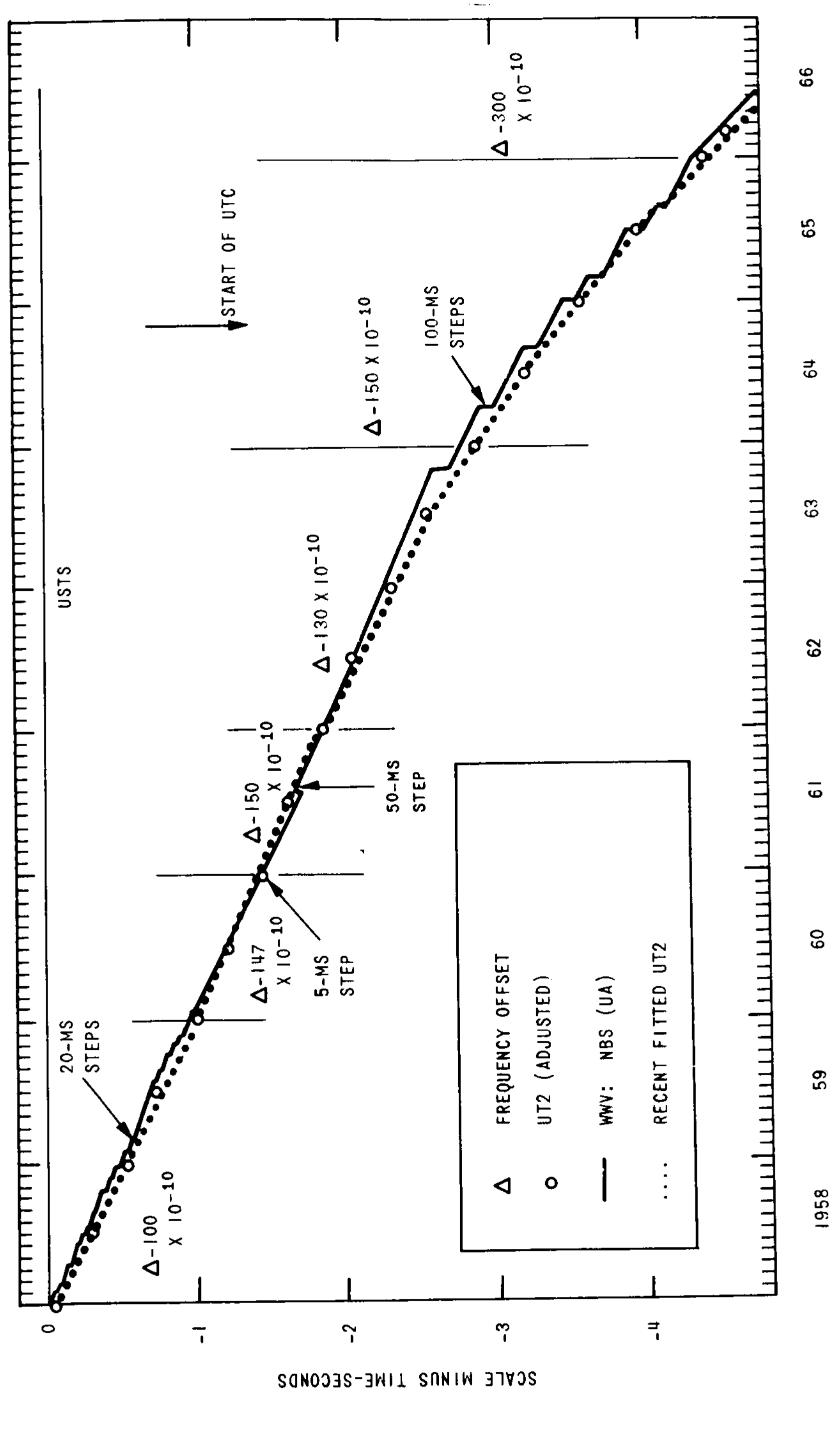


FIGURE 1. TIME DIVERGENCE OF UT2 AND WWV SINCE 1958

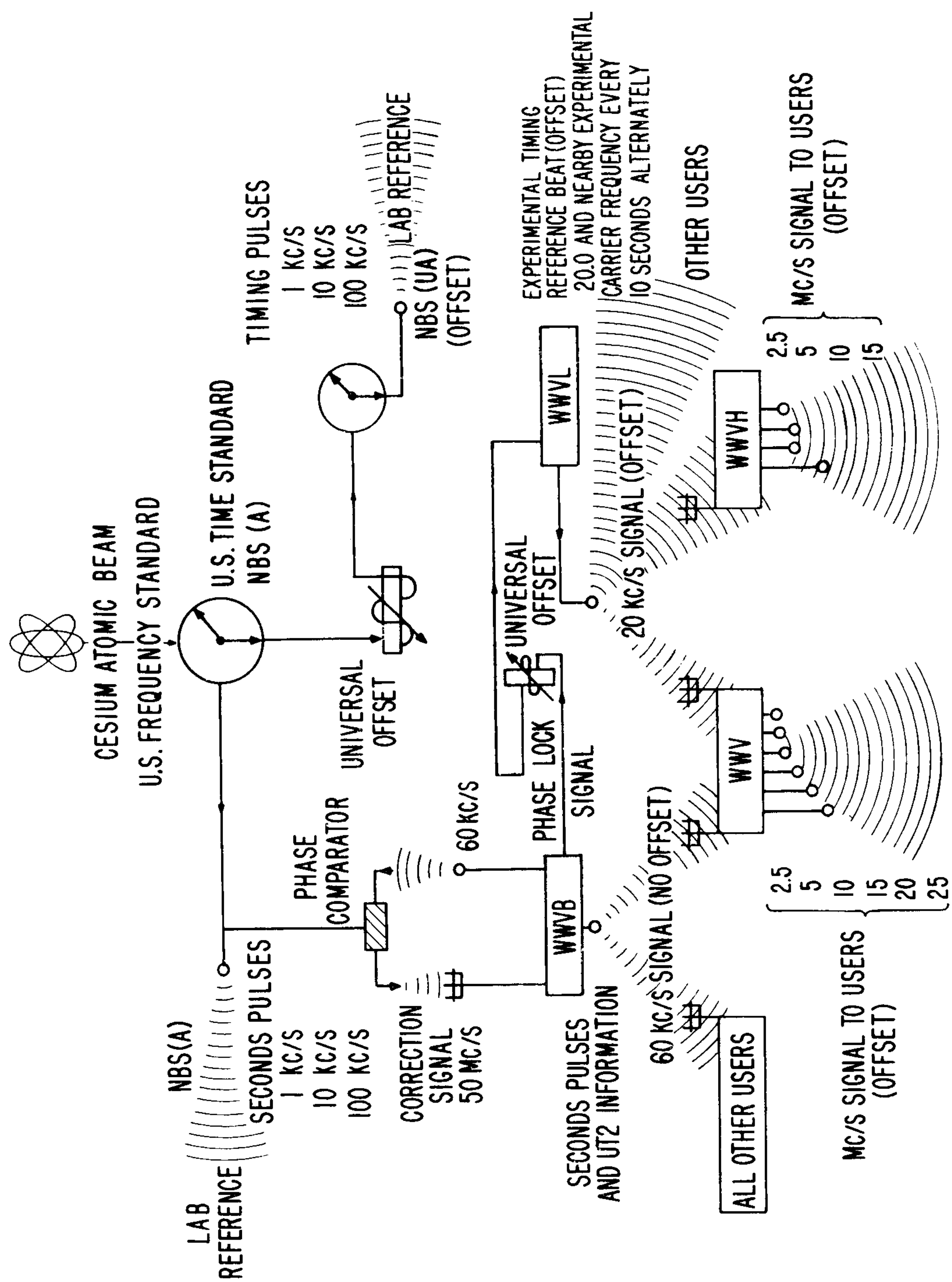
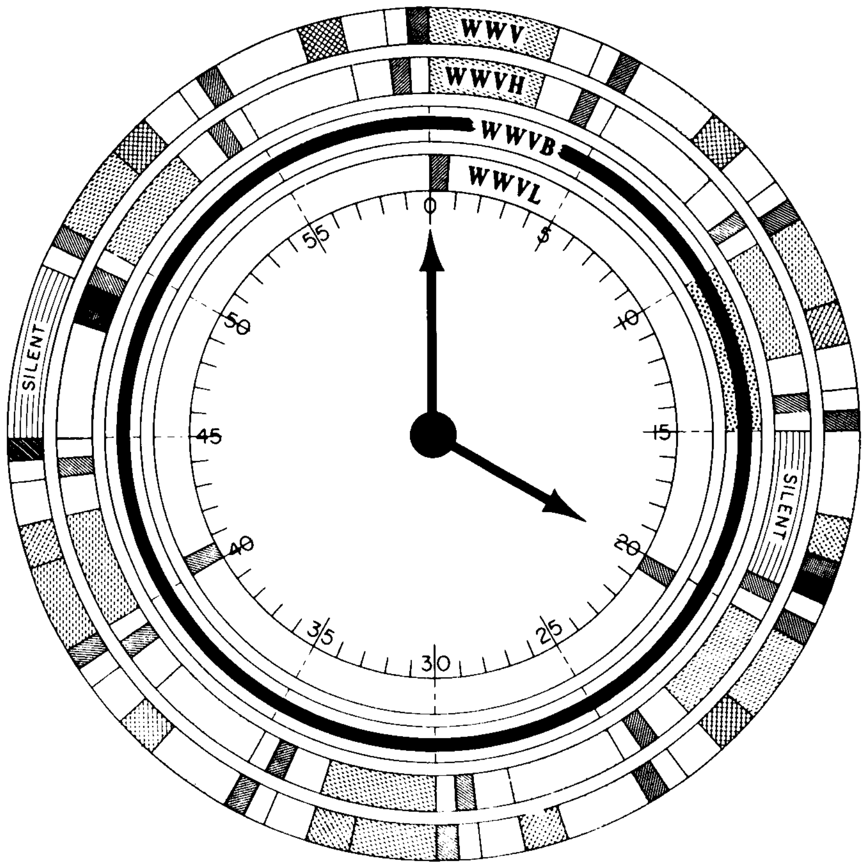


FIGURE 2. NATIONAL BUREAU OF STANDARDS FREQUENCY AND TIME CONTROL SYSTEM, BLOCK DIAGRAM



SECONDS PULSES - WWV, WWVH - CONTINUOUS EXCEPT FOR 59th SECOND OF EACH MINUTE AND DURING SILENT PERIODS

WWVB - SPECIAL TIME CODE

WWVL - NONE

STATION ANNOUNCEMENT

WWV - MORSE CODE - CALL LETTERS, UNIVERSAL TIME, PROPAGATION FORECAST
VOICE - EASTERN STANDARD TIME
MORSE CODE - FREQUENCY OFFSET (ON THE HOUR ONLY)

WWVH - MORSE CODE - CALL LETTERS, UNIVERSAL TIME,
VOICE - HAWAIIAN STANDARD TIME
MORSE CODE - FREQUENCY OFFSET (ON THE HOUR ONLY)

WWVL - MORSE CODE - CALL LETTERS, FREQUENCY OFFSET

100 PPS 1000 Hz MODULATION WWV TIMING CODE

TONE MODULATION 600 Hz

TONE MODULATION 440 Hz

GEOALERTS

IDENTIFICATION PHASE SHIFT

UT-2 TIME CORRECTION

SPECIAL TIME CODE

FIGURE 3. HOURLY BROADCAST SCHEDULES OF WWV, WWVH, WWVB, AND WWVL

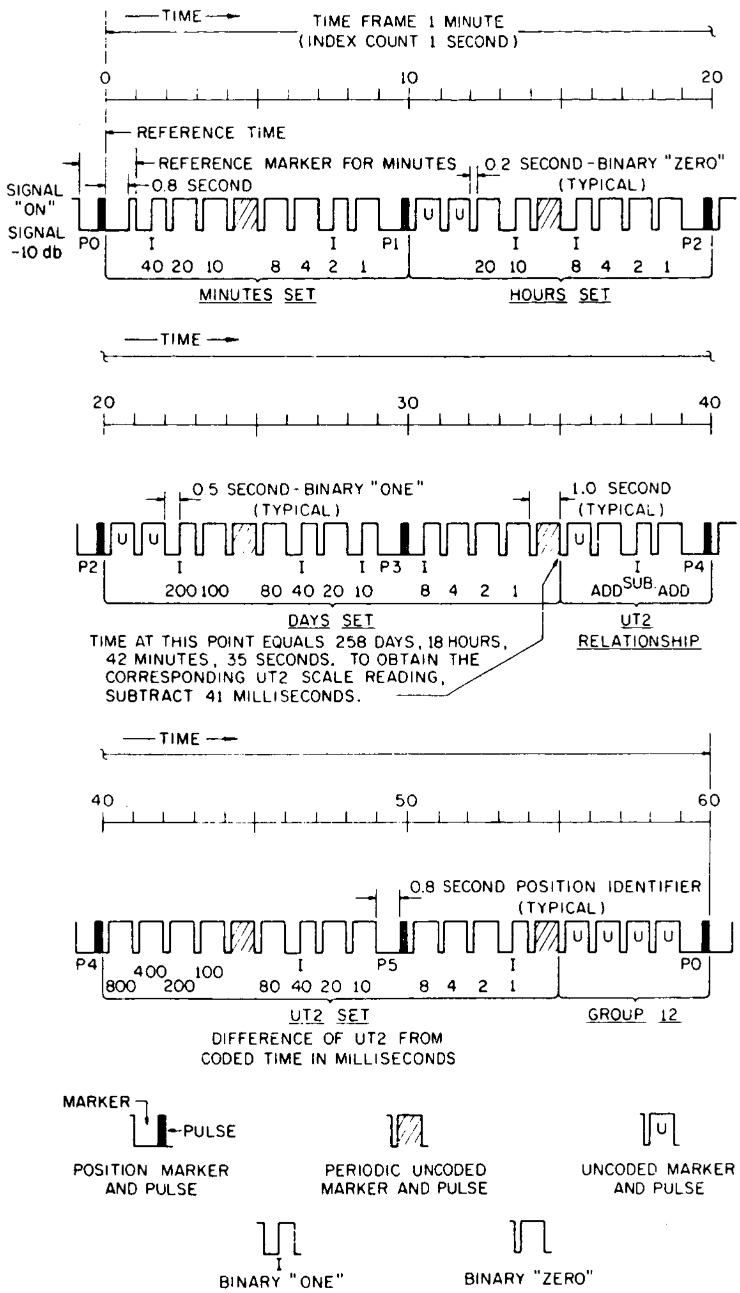


FIGURE 4. NBS TIME CODE FORMAT FOR WWVB (1-PPS)

SECTION III

PROPAGATION CHARACTERISTICS OF ELECTROMAGNETIC WAVES

A. INTRODUCTION

The propagation characteristics of electromagnetic waves are vastly different at different frequencies. This great variation is caused by the properties of the earth, atmosphere, and ionosphere lying in the propagation path, as well as by the physical limitations on the transmitting antenna structures. A number of references treat the subject of wave propagation in depth (refs. 4, 35, 65, 88 and 130). This section is limited to a discussion of those propagation characteristics directly relating to the clock synchronization problem.

B. MAJOR FACTORS AFFECTING PROPAGATION

In a vacuum electromagnetic waves propagate in a regular manner with a spherical wavefront moving at the velocity of light (299,792.50 km/sec). For propagation in any other medium the velocity is slower, and inhomogeneous media such as air or the ionosphere introduce distortion into the wavefront.

1. Effects of Earth's Surface

At low frequencies the surface of the earth presents a discontinuity that causes bending of the wavefront in order to follow the curvature of the earth, thereby producing a "surface" or "ground" wave. This wave penetrates the earth to a depth which is inversely proportional to the square root of the product of the signal frequency and earth conductivity. Attenuation of the groundwave increases with increasing frequency and increases with decreasing conductivity. The practical significance of these characteristics is that higher frequencies are attenuated more rapidly than lower frequencies, and that this effect is more pronounced over land than over sea water. As a result, groundwave signals are useful principally at low and medium frequencies.

Almost invariably groundwaves are vertically polarized (E-field). Because of the "mirror" effect of the conducting earth, a horizontal dipole close to the earth's surface has practically no radiation in the horizontal direction. For the same reason, any horizontally polarized fields generated are, for the most part, cancelled close to the ground by the induced currents in the earth.

Once a wave path has propagated several wavelengths above ground, the influence of the earth is greatly reduced. At high frequencies this is accomplished by aiming the transmitting antenna upward at an angle, while at very high frequencies it is only necessary to assure that the path followed by the wave does not intersect the earth. Since the free space wave is not affected by the earth, its polarization may be in any direction - as determined by the transmitting antenna.

2. Effects of Ionosphere

The ionosphere also presents a discontinuity which affects the propagation of the waves. At very low frequencies the D-layer (70 to 90 km high) provides a relatively smooth reflecting (refracting) surface with relatively low absorption of the waves. Absorption increases in the daytime, when the height of the ionosphere is lower (70 km), and increases with increasing frequency.

At medium and higher frequencies (above 300 kHz) reflection does not take place in the D-layer but at the E-layer (125 km) and at the F-layer (200 to 400 km). Higher and higher frequencies penetrate further into the ionosphere until above a certain frequency waves are not reflected from the F-layer; this frequency is (approximately) the Maximum Usable Frequency (MUF), which is the subject of CRPL ionospheric predictions.

Under differing conditions the signal received at a given point may be a combination of groundwaves and skywaves, or a direct wave and a reflected wave from the ground.

C. PROPAGATION CHARACTERISTICS OF MAJOR FREQUENCY BANDS

The characteristics of propagation in the five important frequency bands will now be described briefly.

1. Very Low Frequency Band:

VLF (f = 3-30 kHz; λ = 100,000 - 10,000 m)

Since at very low frequencies both the earth and ionsphere appear as relatively smooth conducting surfaces, it is convenient to regard the space between them as a waveguide. This, of course, is only an approximation because both earth and ionosphere are neither perfectly smooth nor perfectly conducting. For certain applications it is convenient to use the "wave theory" approach to the analysis of VLF propagation. This approach treats the groundwave and skywave modes separately and considers their composite effect.

The portion of the VLF band used for narrow bandwidth communication and navigation only extends down to the vicinity of 10 kHz. This lower limitation is caused by the combination of transmitting antenna characteristics and propagation effects. All practical ground transmitting antennas at VLF are electrically short since a wavelength is in the order of 20,000 meters. At these wavelengths only vertically polarized waves can be propagated in the horizontal direction since the conducting earth effectively short-circuits any horizontally polarized waves. Thus antennas are vertical monopoles with the earth forming the other half of the dipole. Such an antenna has a high capacitive reactance and a low radiation resistance which, when tuned to resonance with a large inductor (Helix), produces a high-Q circuit that severely limits the bandwidth of the transmitted signal. The antenna reactance, and hence the Q, is inversely proportional to frequency. For a given Q, the absolute bandwidth is inversely proportional to frequency; therefore, the antenna bandwidth is inversely proportional to f^2. An example of the effect of this characteristic is that, even with an elaborate (and expensive) antenna system, the pulses radiated by NBA, Balboa, Panama Canal Zone, have a rise-time greater than 10 milliseconds at a frequency of 24 kHz.

Many papers have been written on the mode theory of VLF propagation. One of the most readable is NBS Technical Note 300 (ref. 130) in which Wait presents graphically the results of theoretical calculations and compares his theoretical work with experimental data taken from a number of sources. Figures 5, 6, 7, 8 and 9 taken from the Note, show the variation of amplitude and phase velocity as a function of frequency over the usual range of interest. The theoretical curves are seen to correspond closely to experimental data. Several important features of the curves are noteworthy: Figures 7 and 8 show that attenuation reaches a minimum value of about 2.5 db per 1000 km at a frequency of approximately 16 kHz in the daytime and close to 1.5 db/1000 km at 14 kHz at night. For this reason these frequencies are useful for long distance communication but - because of the bandwidth problem - only at slow data rates.

The theory and experimental results also show that there is a marked effect of the earth's magnetic field on the amplitude of the VLF signal (figure 9). When the north-south attenuation is 2.5 db per 1000 km, the attenuation west to east is 2.0 db per 1000/cm and the attenuation east to west is 3.0 db per 1000 km.

The apparent phase velocity is a function of the frequency and time of day, as shown in figure 5; it also varies with earth conductivity, as shown in figure 6.

Use of ray theory, in which the groundwave and various skywave modes are treated separately, is sometimes useful in the analysis of particular problems. Figures 10 and 11 taken from Norton (ref. 89), show the amplitude of the various modes at 20 kHz out to a distance of 7000 miles. These graphs illustrate vividly the attractiveness of the mode theory since at distances beyond approximately 2000 miles three or four skywave modes are nearly equal in amplitude. The resultant signal depends upon the relative phase of the various components, which is difficult to determine accurately.

The stability of long distance progagation of VLF was first reported in 1955 by Pierce (refs. 100 and 101) who used the VLF signals from GBR to compare frequency standards. Since then many studies have been performed by different groups - particularly Crombie, Brady, and Steele (refs. 3, 9, 18, 20, 21, 22, 26, 27, 32, 33, 34, 57, 106, 112 and 127) - which confirm the fact that the phase of a VLF signal is quite stable during daylight hours and that the diurnal shift is predictable, within microseconds. The VLF signal phase and amplitude are affected by solar flares and other phenomena which disturb the ionosphere (ref. 27), thereby producing phase errors in the order of 10 microseconds.

The OMEGA system has undergone tests of its propagation stability over the past six years (refs. 23, 86, 96, 116, and 120). The latest data show an rms phase variation over long paths at a frequency of 10.2 kHz of about 5 microseconds in the daytime and 10 microseconds at night.

2. Low Frequency Band:

   LF (f = 30-300 kHz, λ = 10,000-1000 m)

The low frequency band is useful for medium range, moderate bandwidth transmission. Antennas with reasonable electrical characteristics are practical; groundwave propagation to ranges in the order of 1000 miles is feasible; and skywave propagation at night to distant (over 3000 miles) ranges is possible. The wider bandwidth available makes it useful for audio broadcasting in Europe, facsimile communication, high speed teletype, and radio navigation (Loran-C, Decca).

Attenuation of the groundwave signal over both land and sea water is low enough to provide coverage out to distances useful for navigation and timing. The Decca navigation system, a cw hyperbolic system operating on frequencies between 80 kHz and 130 kHz, obtains accurate groundwave signals out to ranges of 300 miles in the daytime, but at night interference from stronger skywaves produces errors at distances beyond 100 miles.

By using larger, wider-band antennas and high power transmitters, Loran-C extends groundwave pulse coverage up to 1500 miles over water. The pulse technique employed in this system permits discrimination between groundwave and delayed skywave.

The D-layer of the ionosphere (which reflects the LF signals) is relatively stable. The effective height of this layer changes from 70 km in the daytime to 90 km at night - taking from one-half to several hours depending upon the particular propagation path. Daytime absorption in the D-region increases with frequency; thus, the difference between day and night skywaves is quite pronounced at the higher end of the LF band. Zones of interference of groundwave and skywave cw signals - while not numerous - tend to be stable, producing some relatively fixed areas of poor signal reception.

3. Medium Frequency Band:

MF (f = 300-3000 kHz; λ = 1000-100 m)

Medium frequencies are used for standard broadcast (535 to 1605 kHz) with medium bandwidth (5 kHz) and efficient, relatively small vertical antennas. Attenuation of the groundwave is relatively high over land and absorption of the daytime skywave is also quite high, causing overland daytime propagation to be quite restricted. At night absorption in the D-layer decreases markedly so that reflections from the E- and F-layers can occur, producing strong nighttime skywaves.

The lower end of the band is used for maritime mobile service since good efficiency is obtainable here from relatively simple shipboard antennas. (The International Distress Frequency is 500 kHz.) Loran-A (1850 and 1950 kHz), with a groundwave range of 800 miles over sea but less than 150 miles over land, is strictly a maritime navigation system.

The various propagation modes of Loran, typical of propagation at night at 2 MHz, are illustrated by figure 12, after Pierce (ref. 102). At lower frequencies there is greater reflection at the E-layer; at higher frequencies, less.

4. High Frequency Band:

HF (f = 3-30 MHz; λ = 100-10 m)

Groundwave attenuation above 3 MHz is so severe that it is practically useless for long range propagation. Both horizontal and vertical polarization are used, depending upon the application. Skywave signals are strong up to the maximum usable frequency (MUF), which depends upon the distance covered, time of day, and season. The MUF and optimum frequency (FOT) for two typical paths are shown in figures 13 and 14, taken from the "Handbook for CRPL Ionospheric Predictions"(ref. 98). It is important to note that the optimum frequency may vary from less than 5 kHz to more than 30 kHz, depending upon the time of day and path length. Considerable seasonal variability will also result, particularly on long east-west paths at high latitudes.

Signals may undergo several reflections from the ionosphere and earth and several modes may propagate to any given point. Their amplitude is a function of the efficiency of reflection, which is usually best for grazing angles at the ionosphere. Variations in the reflected signals, combined with interference between propagation modes produce "fading" - indicated by severe fluctuations in amplitude and phase of the HF signals. Because of the shorter wavelengths, these fluctuations are more rapid at high frequencies than at the lower frequencies.

5. Very High Frequency - Ultra High Frequency Band:

VHF-UHF (f = 30-3000 MHz, λ = 10 m-10 cm)

The frequencies in this band all propagate by line-of-sight (they are essentially space waves) except for the lowest VHF frequencies, which are occasionally reflected by the ionosphere. The influence of the ionosphere decreases with increasing frequency, changing from reflection to refraction to negligible effect above approximately 100 MHz (ref. 72).

Since the wavelengths are short, directional antennas with gain are usually used. Horizontal and vertical polarizations are meaningless if the waves are not affected by the earth.

Reflection and refraction in the ionosphere alters the polarization of the wave. For this reason a receiver, to be most effective, may require an antenna capable of responding to different polarizations.

Point-to-point propagation near the ground is usually accomplished by direct line-of-sight. Because the index of refraction of air decreases with increasing altitude, the waves are refracted. This is usually accounted for in calculating line-of-sight on the spherical earth by assuming the earth's radius to be 4/3 the actual radius.

Trans-horizon propagation is obtained, at considerably reduced signal amplitude, by scattering in the troposphere (ref. 6), which is quite reliable; by scattering in the ionosphere, which is less reliable; and by scattering from meteor trails, which is quite intermittent.

D. Diurnal Changes in Propagation

The ionization of the upper atmosphere, which creates the various "layers" of the ionosphere, is caused principally by radiation from the sun. As a result, the character of the ionosphere changes considerably over a diurnal cycle (24 hours), thereby producing corresponding changes in the propagation of waves affected by the ionosphere. These changes appear to be different at different frequencies, as the characteristics of the various layers change.

At its lowest height, the D-layer forms at about 70 km during the daytime. This produces reflection at that level for VLF and LF signals, high attenuation for MF signals, but no pronounced effect on higher frequencies. At night the electrons forming the 70-km layer recombine with other ions, but a layer which has considerably less absorption to LF and MF waves remains at 90 km. The effect at VLF is the well-known "diurnal shift," a change in phase (or velocity) of the VLF signal which is a function of the amount of the propagation path illuminated by the sun. Figures 15 and 16 - taken from Brady, et. al. (refs. 21 and 22) - show the variation in phase of NBA at Boulder, Colorado and Frankfurt, Germany. It is important to note that while the shorter and more nearly north-south path to Boulder shows fairly stable daytime and nighttime periods all year, the longer west-east path to Frankfurt shows no stable night period in the summer and very little stable day period in the winter. The shift from day to night is approximately 170 to 200 degrees (26 to 31 microseconds) at Boulder and 400 to 500 degrees (62 to 77 microseconds) at Frankfurt.

Typically, night propagation exhibits greater variation than day - exhibiting standard deviations of the shift on a monthly basis, typically 3 to 4 microseconds at night and 1 to 2 microseconds in the daytime at Boulder. At Frankfurt, the deviations were 7 to 9 microseconds at night and 1 to 3 microseconds in the daytime. The lower deviations in the daytime make that the obvious first choice as a time for phase comparison.

The effect on LF signals is similar, except that the absorption of the daytime D-layer is greater - especially at the higher end of the band.

At HF the effect is not so much a change in effective height as it is a change in the critical frequency - the highest frequency reflected by the F-layer. This is the maximum usable frequency, which increases at night as the electron density decreases.

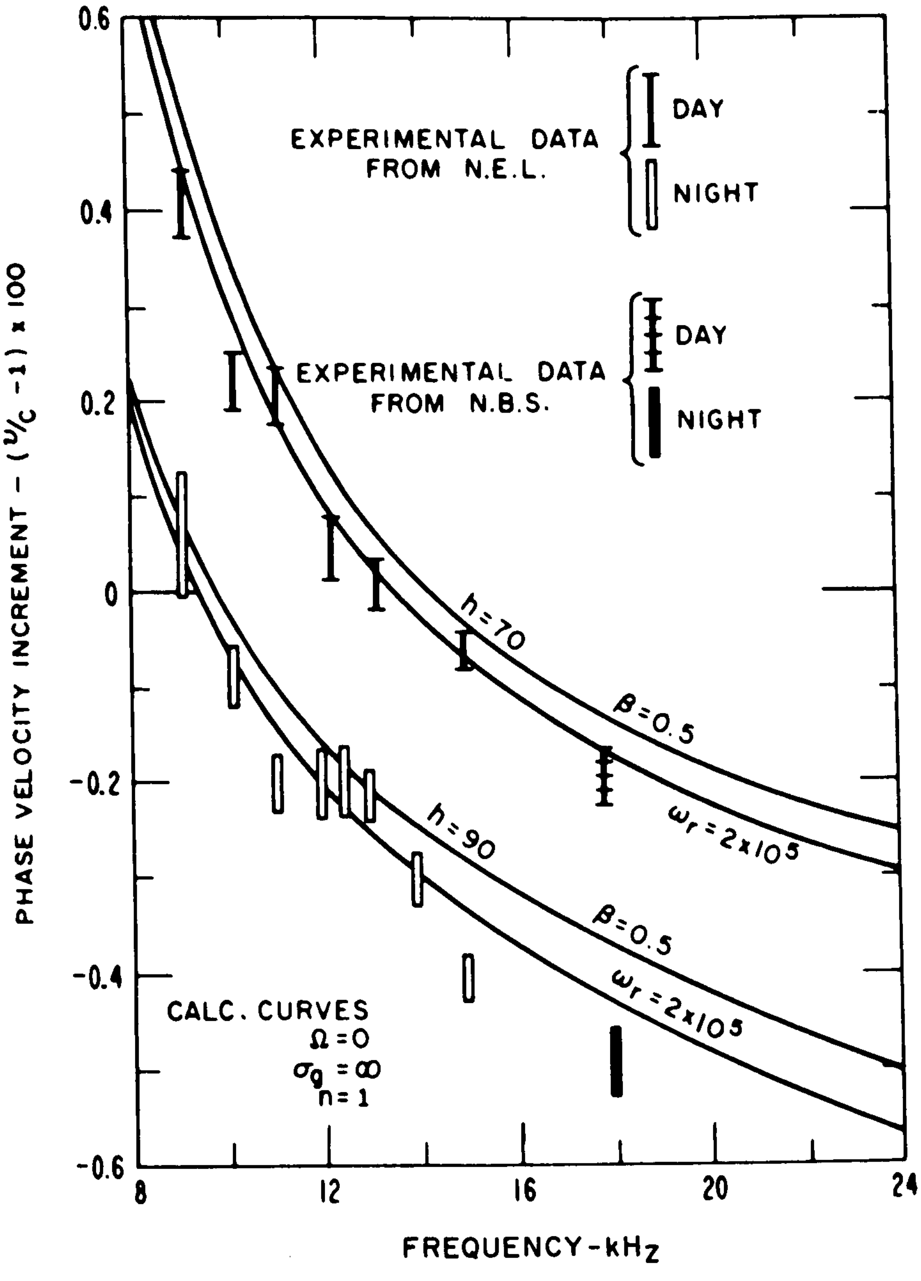


FIGURE 5. APPARENT PHASE VELOCITY INCREMENT VS FREQUENCY

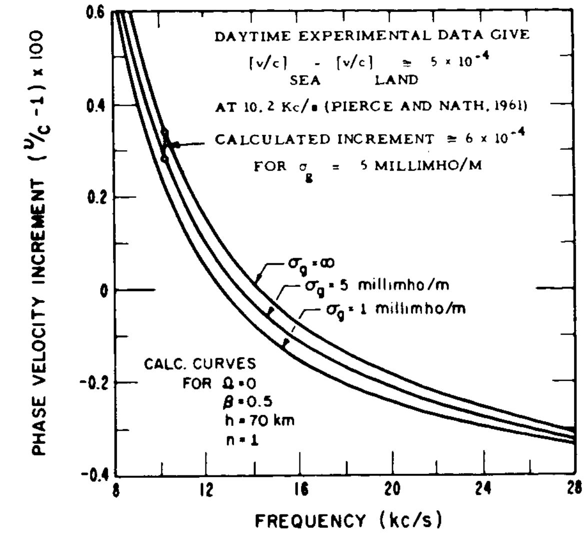


FIGURE 6. APPARENT PHASE VELOCITY INCREMENT VS FREQUENCY FOR DIFFERENT EARTH CONDUCTIVITIES

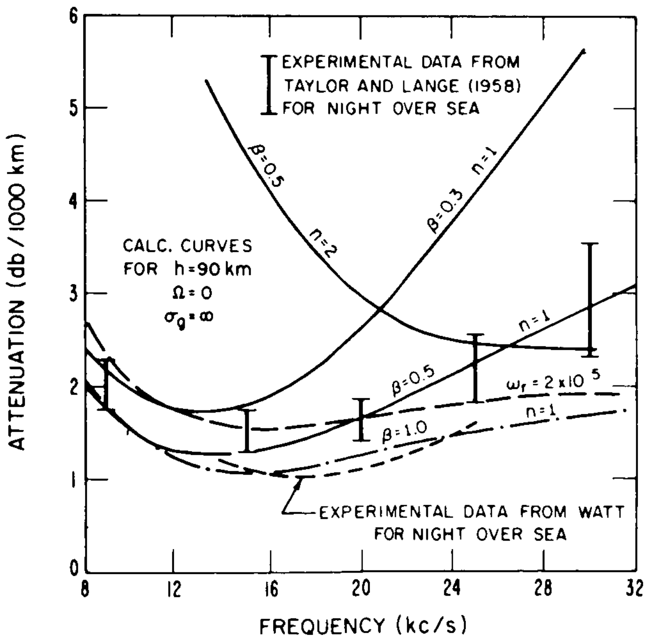


FIGURE 7. APPARENT ATTENUATION RATE VS FREQUENCY AT NIGHT OVER SEA

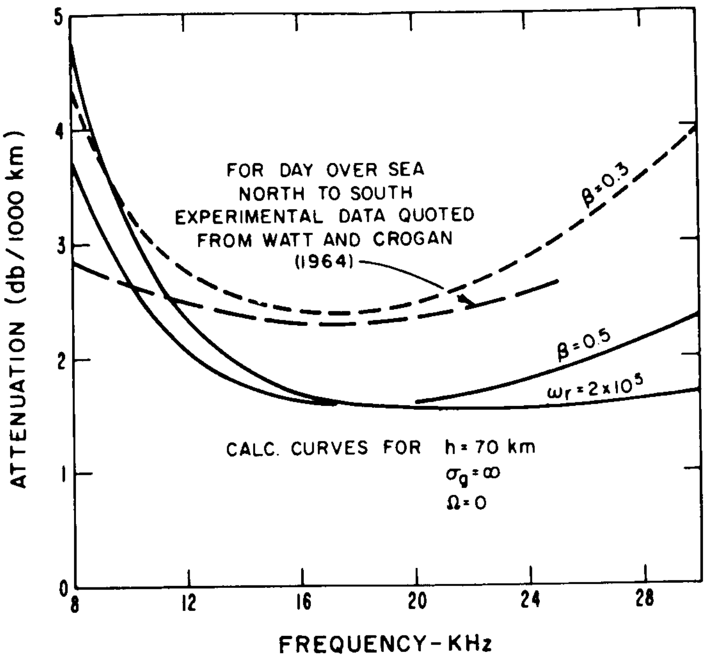


FIGURE 8. APPARENT ATTENUATION RATE VS FREQUENCY FOR DAYTIME OVER SEA (NORTH-TO-SOUTH TRANSMISSION)

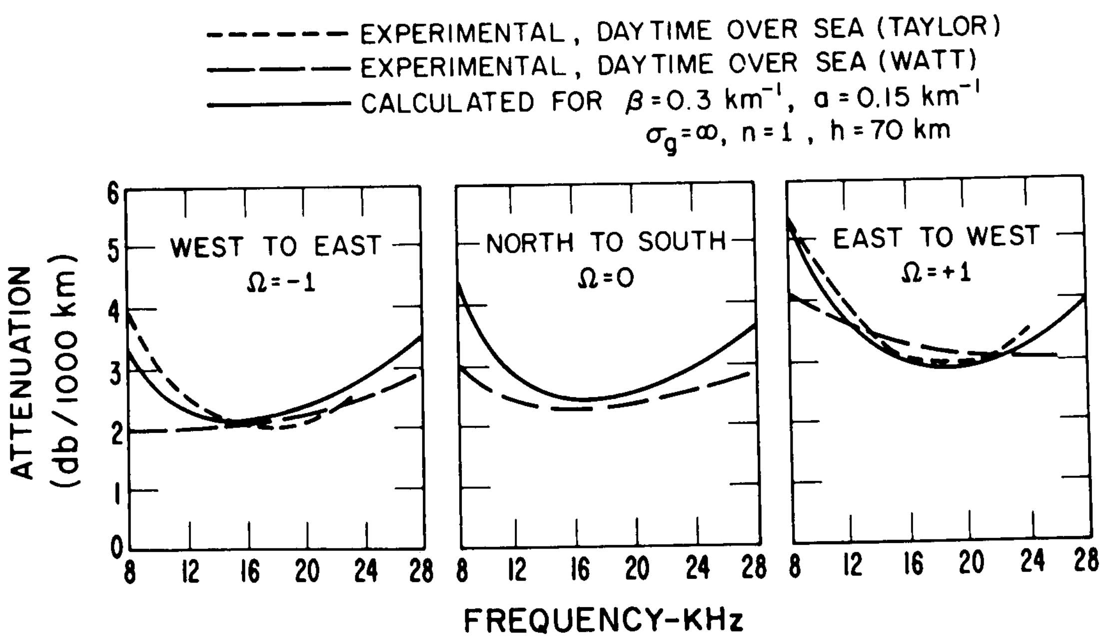


FIGURE 9. APPARENT ATTENUATION RATE VS FREQUENCY FOR DIFFERENT AZIMUTHS

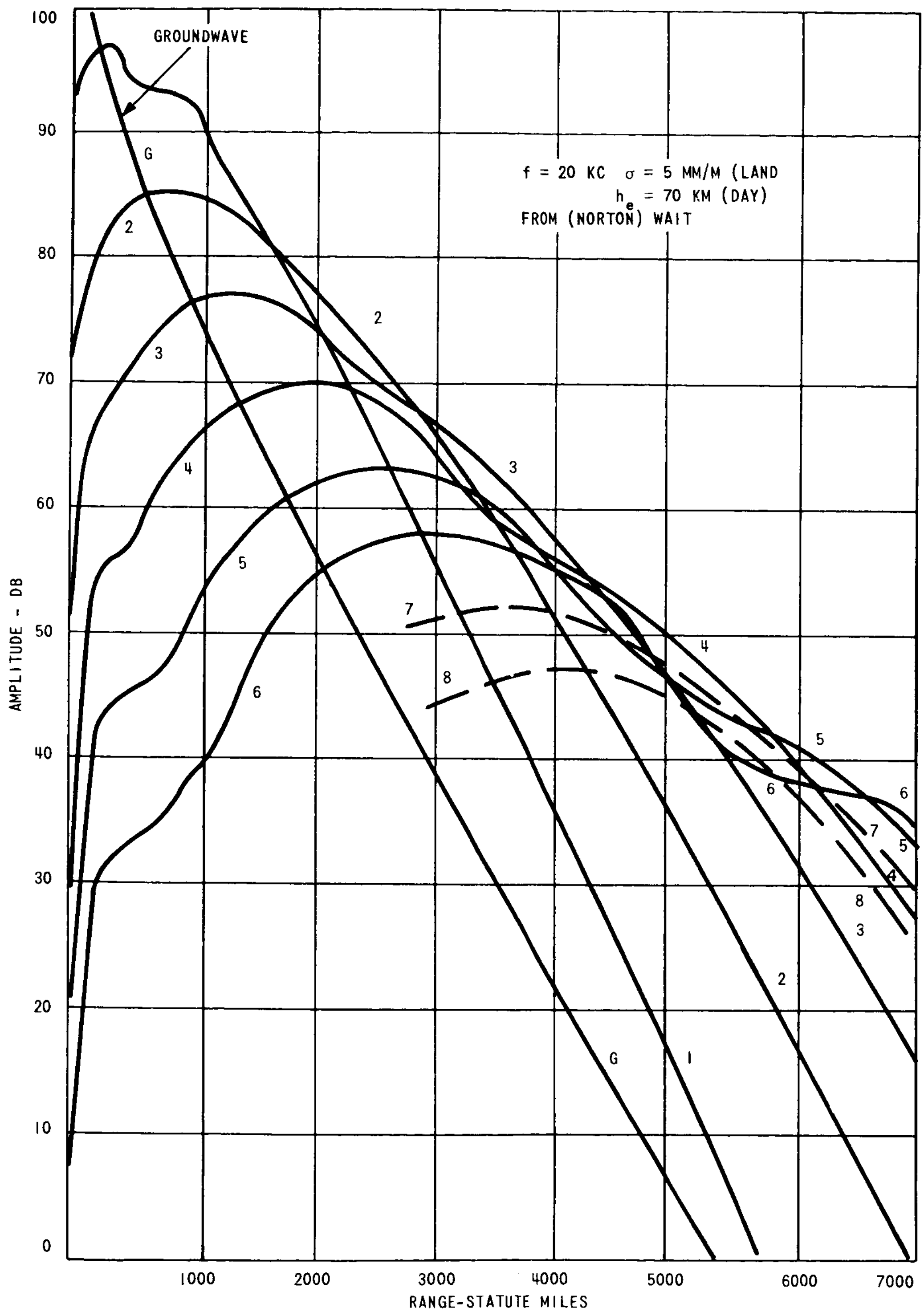


FIGURE 10 RELATIVE 20-KHz SKYWAVE AND GROUNDWAVE AMPLITUDE VS RANGE FOR DAYTIME OVER LAND

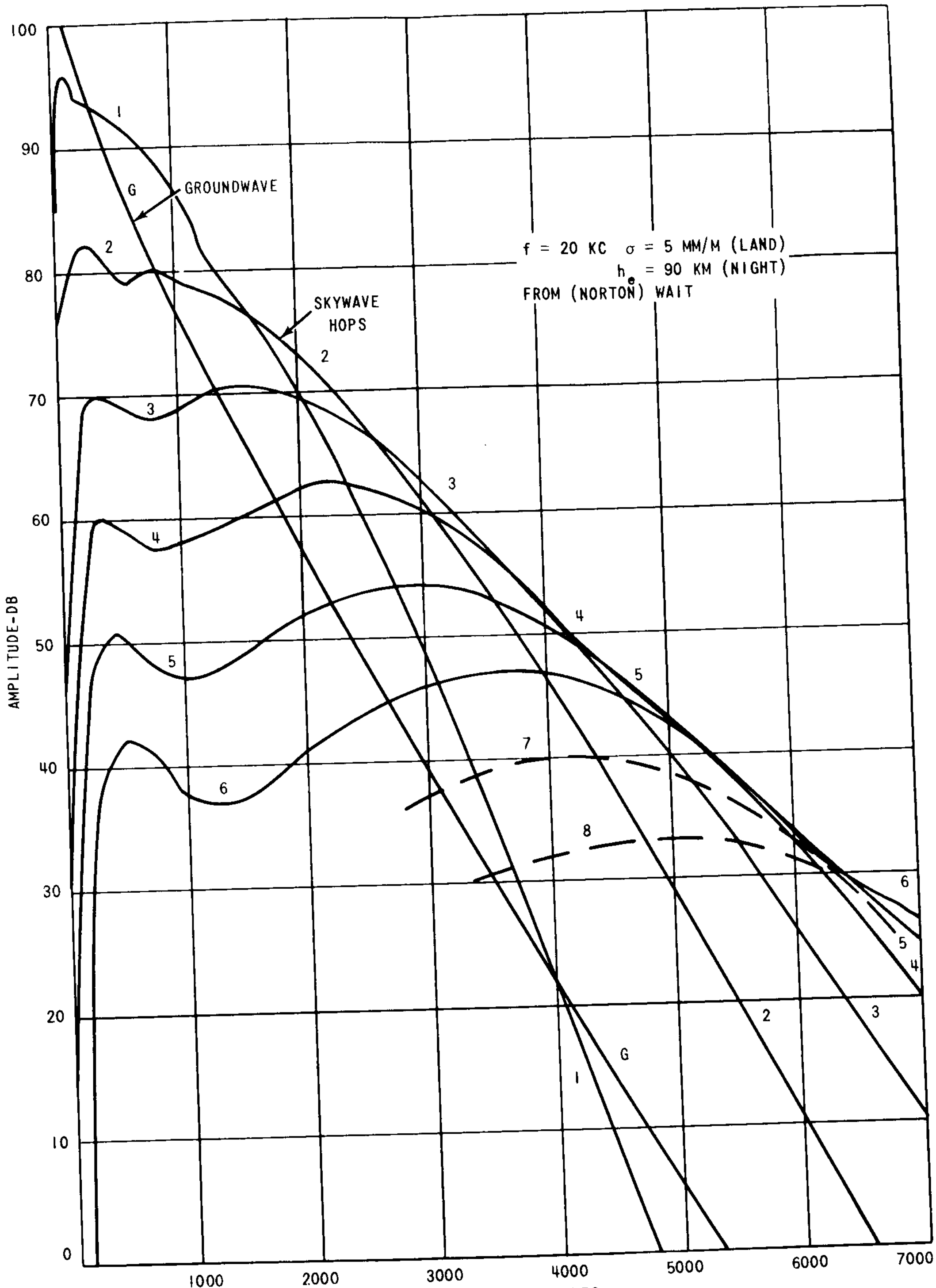


FIGURE 11. RELATIVE 20-KH$_Z$ SKYWAVE AND GROUNDWAVE AMPLITUDE VS RANGE AT NIGHT OVER LAND

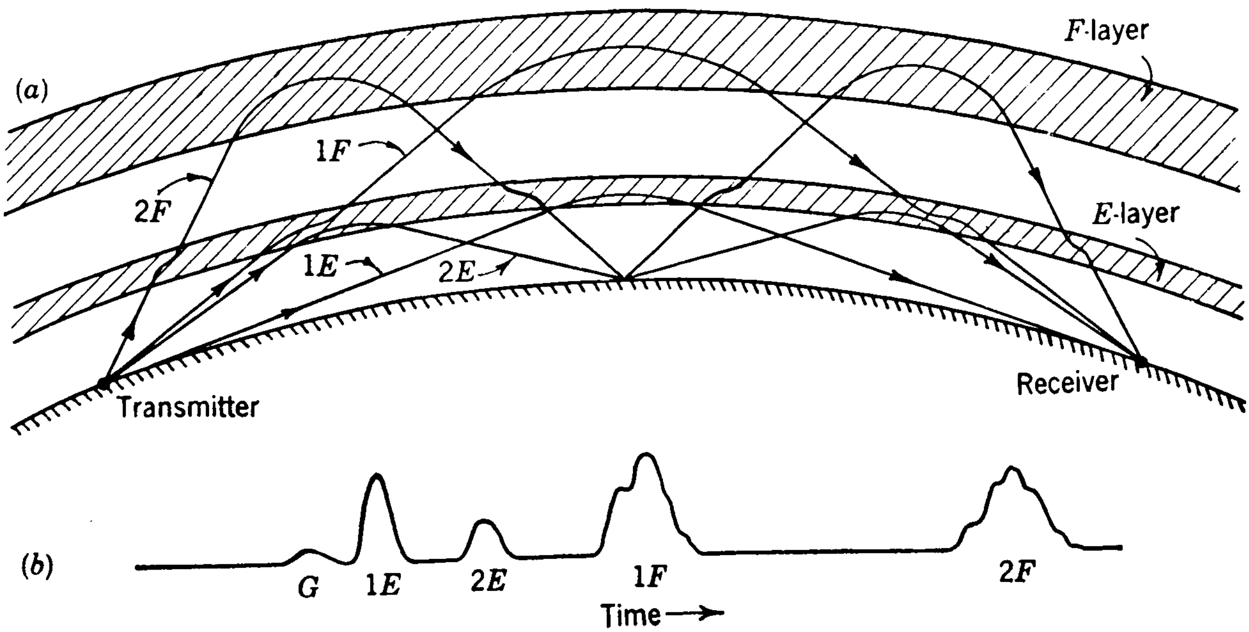


FIGURE 12. LORAN PROPAGATION MODES FOR 2MHz AT NIGHT

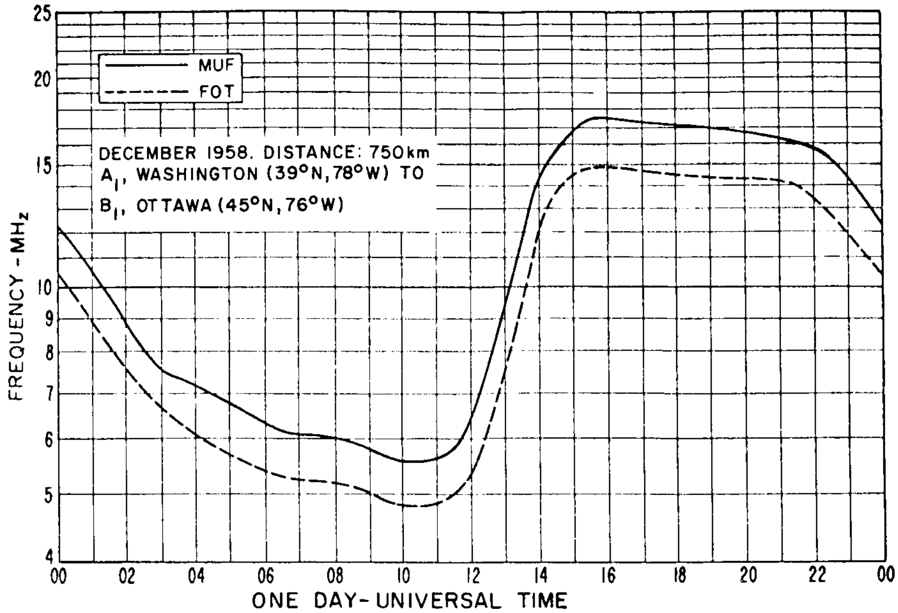


FIGURE 13. MAXIMUM USABLE FREQUENCY AND OPTIMUM FREQUENCY FOR TYPICAL SHORT PATH

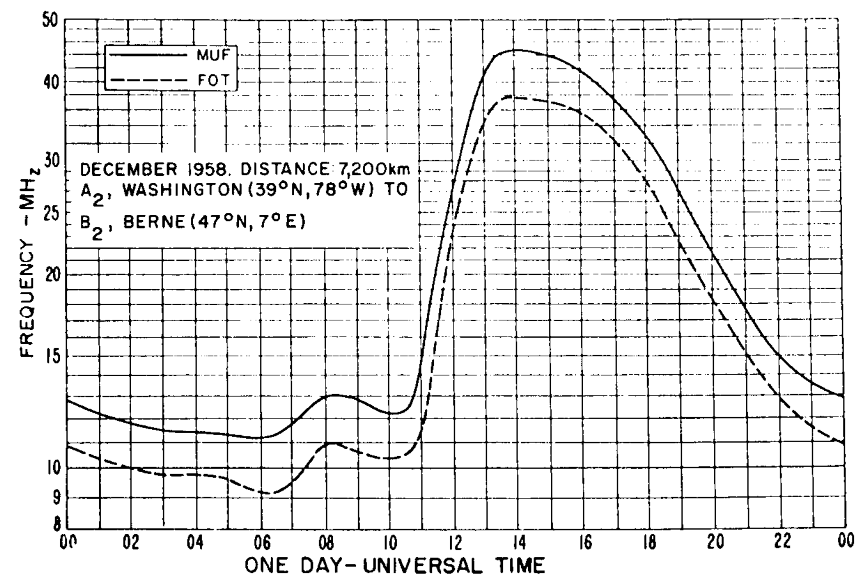


FIGURE 14. MAXIMUM USABLE FREQUENCY AND OPTIMUM FREQUENCY FOR TYPICAL LONG PATH

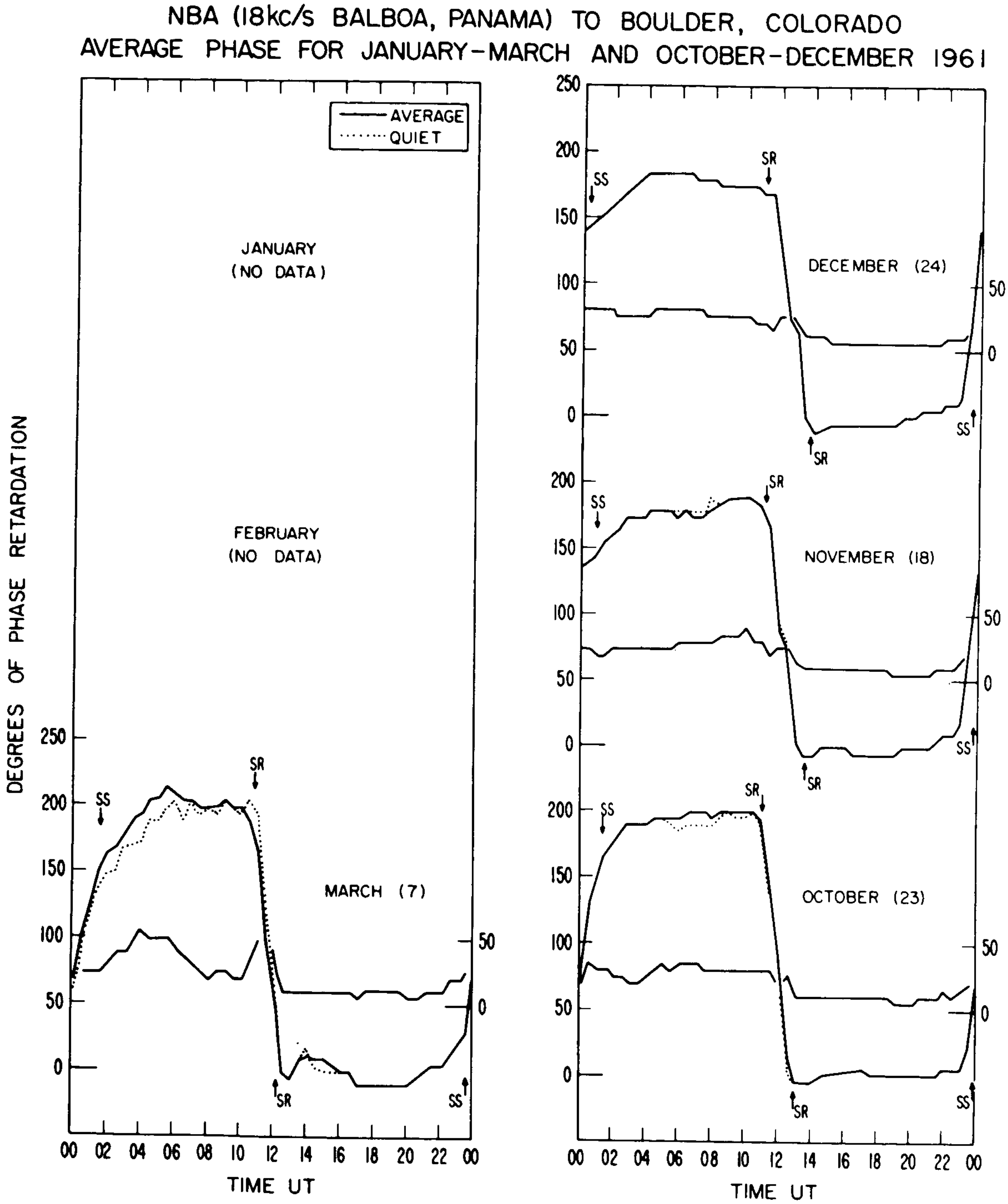


FIGURE 15. MEAN PHASE VARIATIONS AND STANDARD DEVIATIONS IN DEGREES AT BOULDER, COLORADO, FOR JANUARY-MARCH AND OCTOBER-DECEMBER 1961

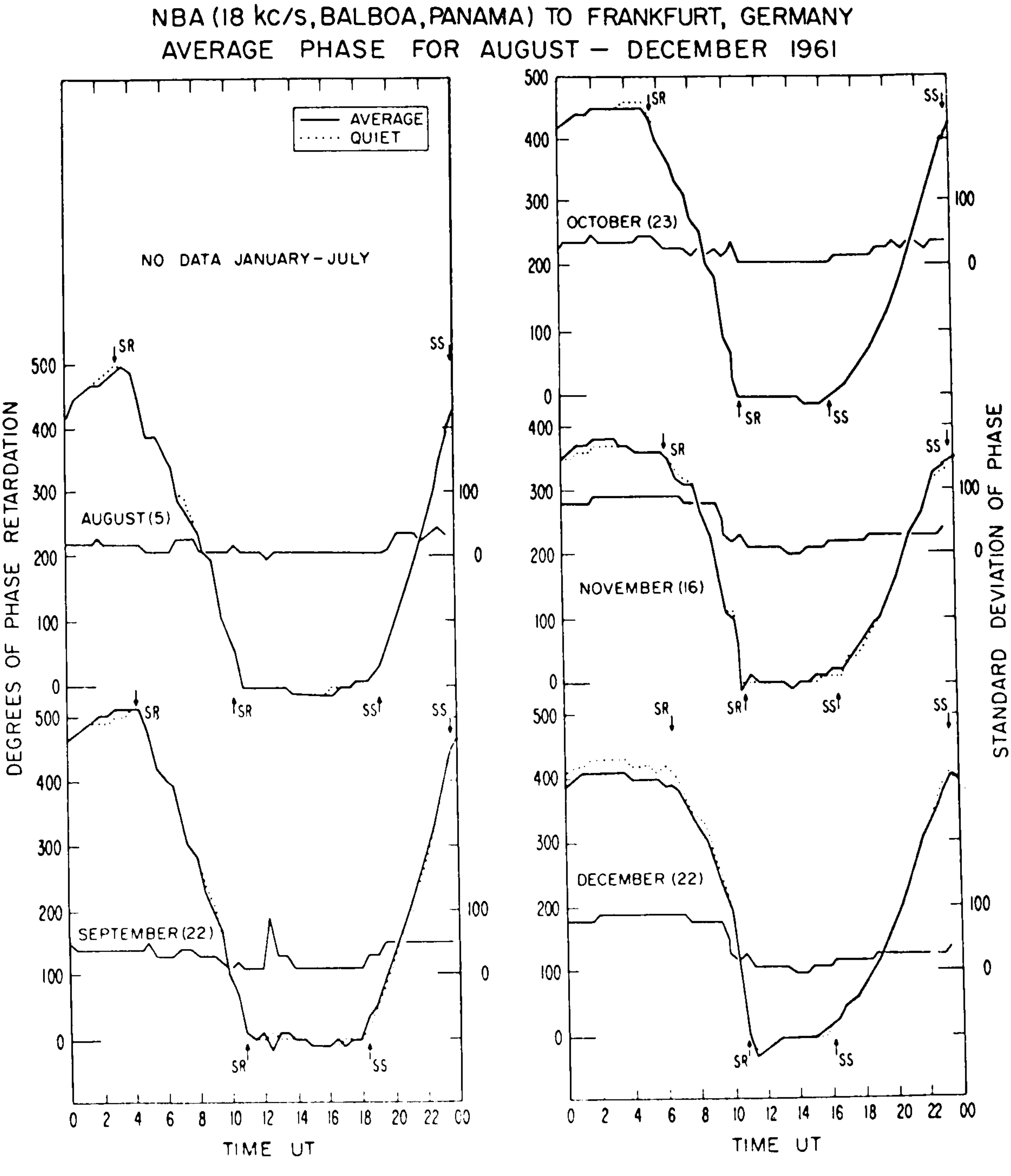


FIGURE 16. MEAN PHASE VARIATIONS AND STANDARD DEVIATIONS IN DEGREES AT FRANKFURT, GERMANY, FOR AUGUST–DECEMBER 1961

SECTION IV

FREQUENCY STANDARDS

A. INTRODUCTION

The basic element for determining the accuracy of any practical clock is a standard frequency source. For the purposes of this study, two basic frequency standards are considered: the crystal oscillator and the "atomic" standard. This section discusses the sources of errors in both of these standards, and describes their use in clocks - both stationary and portable.

The following generally-accepted definitions relating to frequency standards are used in this report:

- Initial Frequency Error - the functional frequency difference, $\Delta f/f$, between the oscillator and an accepted standard at the start of the period under consideration, i.e., where it is equivalent to $(\Delta f/f)_{t_0}$
- Accuracy - the average fractional frequency deviation of an oscillator from an accepted standard of frequency, such as A.1 or UT2
- Precision - the fractional standard deviation of a series of frequency measurements made over a period of hours - with realignment before each measurement, if applicable
- Long Term Stability - the standard deviation of the change in average frequency between successive 30-minute intervals over a period of 1 day (= a)
- Short Term Stability - the standard deviation of a series of frequency measurements made over a period (usually 1 minute).

B. FREQUENCY AND TIME ERROR

The error in the frequency, $\Delta f/f$, supplied by an oscillator can be expressed by the following power series as a function of time:

$$\frac{\Delta f}{f} = \left(\frac{\Delta f}{f}\right)_{t_o} + at + \beta t^2 + --- \tag{1}$$

where

$\frac{\Delta f}{f}_{t_o}$ = initial frequency error

a = linear frequency drift rate

β = frequency acceleration rate.

The time error, τ, accumulated by a clock during time T is given by

$$\tau = \int_o^T \frac{\Delta f}{f} dt = \int_o^T \left[\left(\frac{\Delta f}{f}\right)_{t_o} + at + \beta t^2\right] dt$$

$$= \left(\frac{\Delta f}{f}\right)_{t_o} T \pm \frac{1}{2} aT^2 \pm \frac{1}{3} \beta T^3 \tag{2}$$

The second order term, β, decreases with the aging of a crystal oscillator and does not exist in atomic standards. It can be considered negligibly small.

The variation of T with changes in the first two terms is shown in figures 17 and 18.

If a good quartz crystal oscillator is used. the term $(\Delta f/f)_{t_o}$ can be reduced to about ± 2 to 3×10^{-11} by carefully comparing the time from the clock against a primary time standard for a 24-hour period, and then adjusting the frequency of the oscillator to remove the offset. The term "a" for a quartz oscillator, designated "long term stability" by manufacturers, is typically 1 to 5×10^{-10} per day for a 5-MHz crystal and 5×10^{-11} for a 2.5-MHz crystal. Some manufacturers claim a stability of 1×10^{-11} per day, which is attainable only after a long period of operation in a constant environment.

Considerably better performance can be achieved by the use of frequency standards that are based on atomic resonance. Two kinds of "atomic" frequency standards are available commercially at present: the cesium-beam type and the rubidium-vapor cell type. Each has certain advantages and disadvantages.

The cesium-beam standard, manufactured by Hewlett-Packard Company, (ref. 52) National Company, (refs. 75, 80, and 85) and Pickard and Burns, Inc., has the advantage of being a "primary" standard; that is, when manufactured and adjusted according to specifications, its frequency will be within one part in 10^{-11} of the expected value, and this frequency does not change with time. The frequency accuracy chart of figure 19 shows that 23 cesium-beam tubes were within 4 parts in 10^{-12} of the USFS (ref. 17).

The rubidium-vapor standard, made by General Technology Division of Tracor (ref. 43) and by Varian Associates, is not a primary standard in that its frequency must be adjusted to the prescribed value after manufacture. Once set, the stability can be expected to be as shown in figure 20 in which the short-term stability of the rubidium standard is seen to be better than that of the cesium. Conversely, the long-term stability of the cesium standard is considerably better than that of the rubidium. For nearly all clock uses, the long-term stability is much more important. The values of stability given in figure 20 are obtained from manufacturers' data, but are not guaranteed specifications.

The rubidium standard is tunable over a limited range (4×10^{-9} for the General Technology unit and 1×10^{-8} for the Varian) by variation of the internal magnetic field. Both standards have a frequency variation of less than 5×10^{-12} for changes in orientation of the earth's magnetic field.

As shown in the comparative summary of table 1, the rubidium cell standard has the advantage of smaller size, greater weight, and lower price; however, for high precision over extended periods of time, the stability of the cesium-beam standard (figure 20) is far superior.

TABLE 1. CHARACTERISTICS OF ATOMIC STANDARDS

Cell Element	Manufacturer	Overall Dimensions H x W x D (in.)	Weight (lbs)	Rated Power	Cost per Complete Unit
Cesium	Hewlett-Packard	19 x 19 x 17	63	115/28V 50w	$15,000
Cesium	National Company	7 x 17 x 20	70	115/28V	15,000
Cesium	Pickard and Burns, Inc.	9 x 19 x 22	65	115/28V 85w	15,000
Rubidium	Varian Associates	8 x 5 x 20	20	28V 25w	10,000
Rubidium	General Technology	5 x 16 x 19	40	115/28V 35w	10,000
Rubidium	General Technology*	8 x 5 x 16	45	115/28V 35w	-

*Tactical clock built to MIL-Specifications includes standby batteries.

C. RELIABILITY OF ATOMIC STANDARDS

Both Hewlett-Packard and Pickard and Burns guarantee a 10,000-hour life for the cesium-beam resonator in their frequency standards. National Company states that the "minimum MTBF" of its standard is 10,000 hours. Varian Associates, who supplies the resonators to Hewlett-Packard and Pickard and Burns, guarantees them for 1 year (8760 hours), while National Company quotes a "minimum MTBF" of 3000 hours for the electronics of their portable "Atomnichron" standard.

Hewlett-Packard reports data on their Model 5060A frequency standard, showing 15 failures in 166,742 hours of operation, giving an MTBF of 11,116 hours (1966) (ref. 17).

Separately the limiting factor in the life of the cesium-beam resonator is the depletion of the supply of cesium within the unit.

General Technology has collected reliability data on their model 304-B rubidium standard. The results of these tests show 17 failures in 404,570 hours, giving an MTBF of 23,800 hours as of May 1965. This company claims to have a proprietary manufacturing technique for their rubidium vapor cell, and claims to have had no cells fail in up to 5 years of operation.

D. PORTABLE CLOCK SYNCHRONIZATION

1. Introduction

The portable clock method for synchronizing clocks employs a Master clock to which all of the Slave clocks are set. To do this, the Master clock is physically transported to each of the Slave clocks. Time synchronization is achieved by bringing a timing pulse from the Slave clock either into coincidence with the timing pulse from the Master clock or to a point at a fixed delay from the Master pulse.

The greatest advantage of this technique is that the Slave clocks do not need a timing link to the Master of a type described elsewhere in this study. The disadvantage, of course, is the requirement for physical transport of the Master clock (refs. 5 and 16) to all of the Slaves.

2. Clock Accuracy

The accuracy obtainable is proportional to the amount of money invested. Clocks using cesium-beam frequency standards that are checked every few weeks can have a probable error of less than 1 microsecond. Less expensive clocks, checked less frequently, will have a correspondingly greater error.

The accuracy of the clock is a direct function of the accuracy of the frequency standard driving it. For the Master and portable clocks, the objective of accuracy and reliability must be achieved in spite of the fact that it is being moved. The vibration incident to moving a crystal standard affects the accuracy of the crystal oscillator. The latest models of cesium-beam standards have considerably better stability than the crystal clocks.

To find the probable time error developed by a clock for a given period, figures 17 and 18 are used to find the contribution due to offset and drift rate. Next, the error attributable to each cause is determined, and then the root-sum-square is taken.

The values of $\Delta f/f$ and a, for a typical "best" crystal clock, give values of T after 10 days of 9 and 43 microseconds for a probable value of 44 microseconds. A cesium-beam standard, on the other hand, has a drift of less than 1 microsecond in 10 days.

In general, it is not sensible to transport a crystal clock if the transportation costs are high. A portable crystal clock will cost in the order of \$7,000, while a portable atomic clock may cost about \$20,000. If 10-microsecond time synchronization is required, a cesium-beam Master clock can go for much more than a month without recalibration. The best crystal standards will drift 10 microseconds in about 5 days when used as portable clocks.

Once set, the Slave clock is as good as the phase information made available to it. For example, a VLF tracking receiver, tuned to WWVL (20.0 kHz) and driven from the clock frequency standard, will indicate the time difference in microseconds between the clock and an arbitrary phase of the received signal. Commercially available receivers include a counter which reads the accumulated phase difference in microseconds. It is therefore possible, by tracking WWVL (or any other stabilized VLF station), to read the time drift of the clock and, if desired, to correct it.

Under these conditions a Slave clock, even crystal controlled, can be used to provide microsecond time indefinitely once it has been set. Because the 20-kHz signal has a period (and ambiguity) of 50 microseconds, it is only necessary to track or predict the clock error to ±25 microseconds to be assured of correct time. An estimate of the phase accuracy which can be held in this way can be obtained by reference to the data shown in figures 15 and 16, in which the standard deviations of 18-kHz signals in the daytime were in the order of 1 to 2 microseconds over a medium path and 2 to 3 microseconds over a long path.

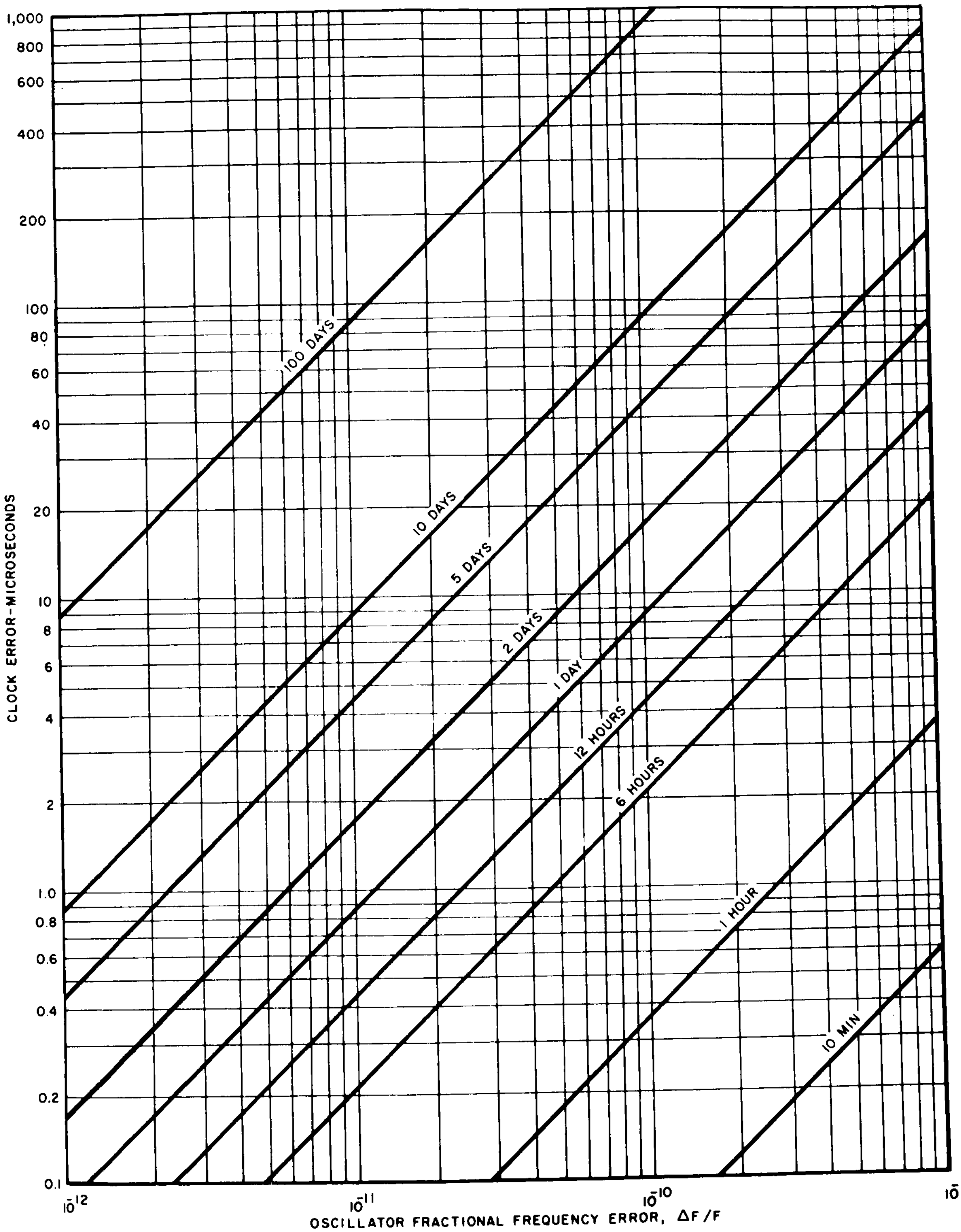


FIGURE 17. CLOCK TIME ERROR VS FREQUENCY OFFSET FOR PERIODS FROM 10 MIN. TO 100 DAYS

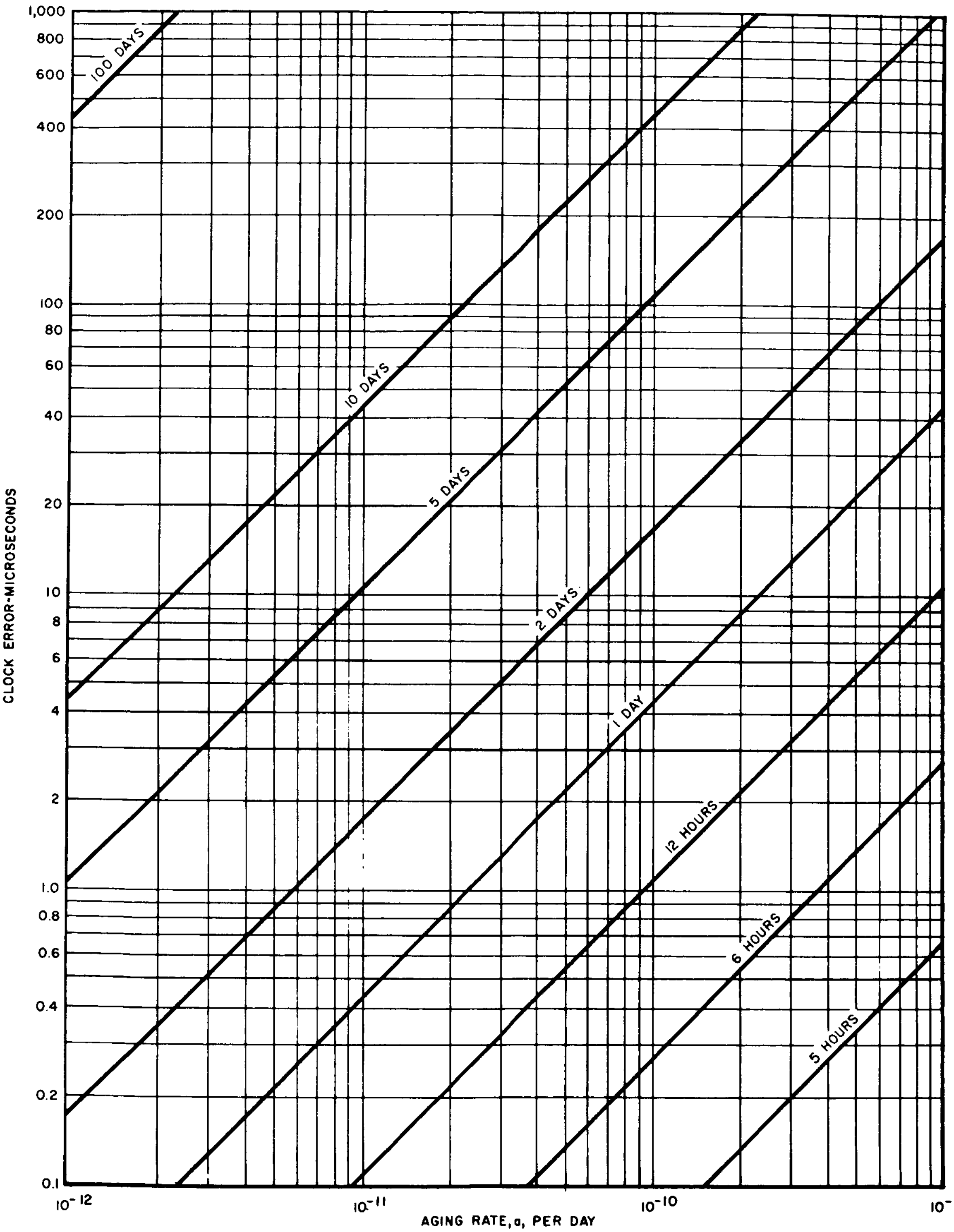


FIGURE 18. CLOCK TIME ERROR VS OSCILLATOR AGING RATE FOR PERIODS FROM 5 HOURS TO 100 DAYS

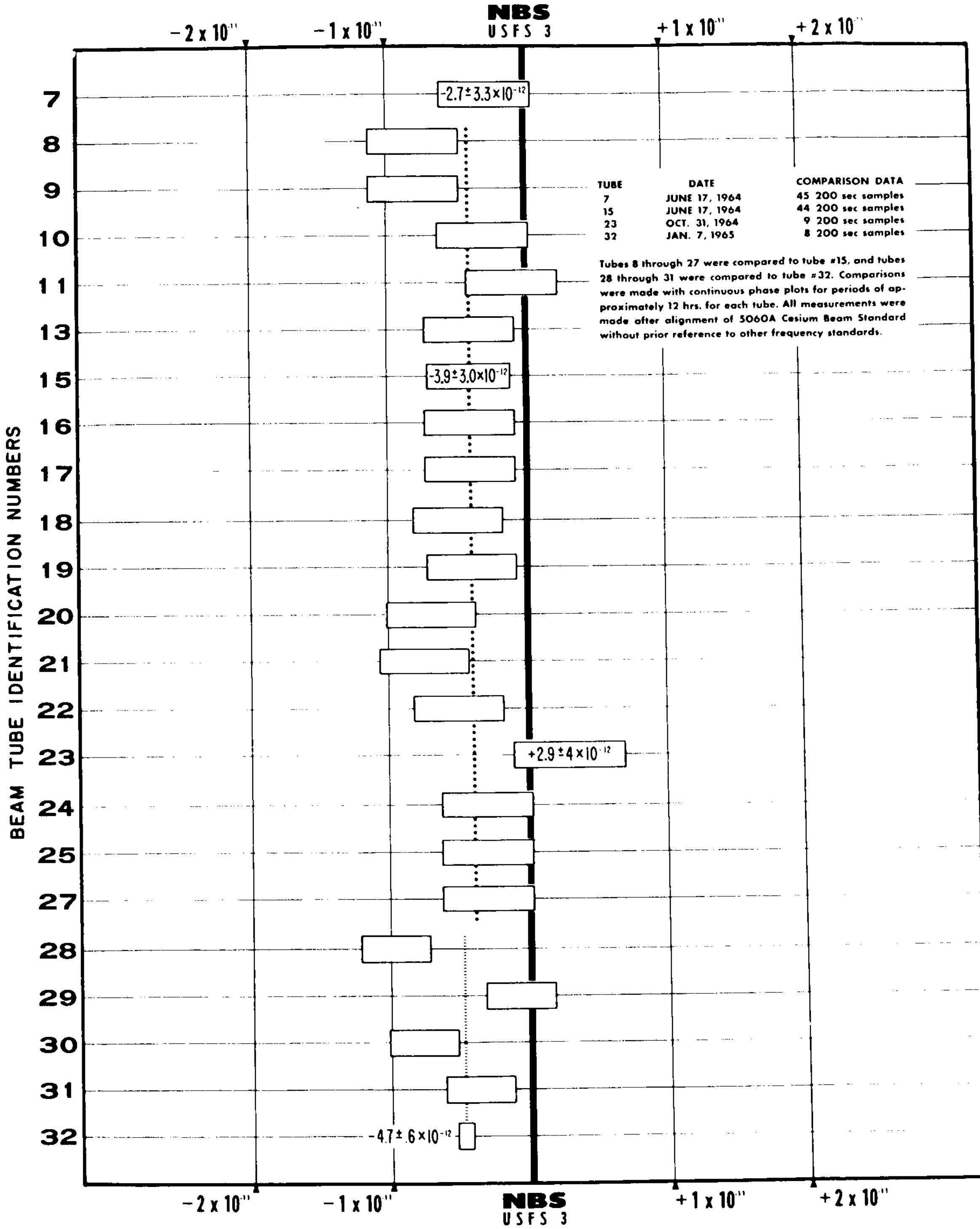


FIGURE 19. FREQUENCY ACCURACY CHART FOR 23 CESIUM BEAM TUBES

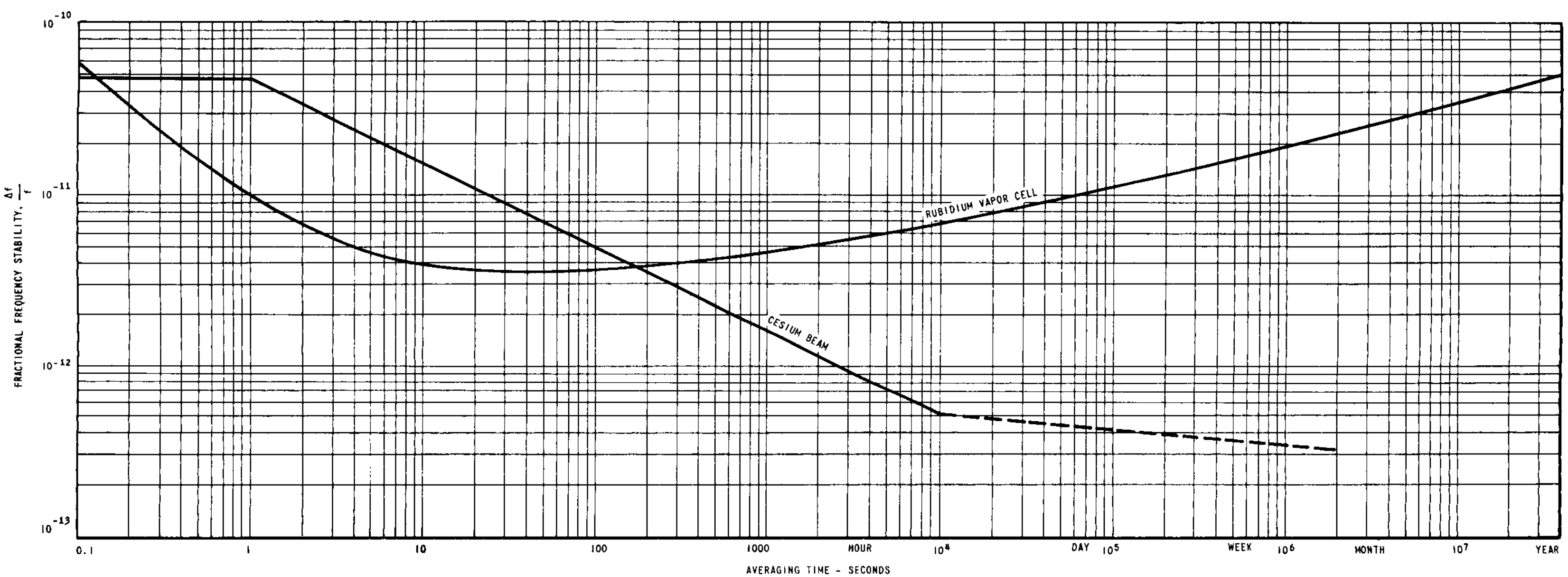


FIGURE 20. STABILITY PLOTS FOR CESIUM BEAM AND RUBIDIUM VAPOR CELL FREQUENCY STANDARDS

SECTION V

VLF CLOCK-SYNCHRONIZATION SYSTEMS

A. INTRODUCTION

Propagation of VLF waves is characterized by low attenuation and excellent stability - at least in the range from 10 to 30 kHz. The VLF band is used for long range communications (to a great extent by the U.S. Navy and to a lesser extent by foreign governments); for long range navigation; for the OMEGA system; and on 20.0 kHz by WWVL, the standard frequency station at Ft. Collins, Colorado.

The principal Navy VLF transmitters - designated as NAA, NBA, NPG/NLK, NPM, and NSS - have their frequencies controlled by reference to the U.S. Naval Observatory, but only NBA transmits a regular 1-second time pulse. The OMEGA system is only partly implemented (there are no receivers generally available) and the system is not yet controlled to Universal Time. The transmissions from WWVL are not time signals, but experiments currently underway are attempting to obtain time information by synchronized transmission on two frequencies. Station GBR at Rugby, England, transmits time signals on 16 kHz which are synchronized to UTC.

Each of the foregoing facilities has the capability to provide clock-synchronization information over wide areas. The characteristics, capabilities, and limitations of each of these facilities are set forth in the following discussion.

B. VLF TIME TRANSMISSIONS

1. Introduction

U.S. Navy Radio Station NBA in Balboa, Canal Zone, operating on a frequency of 24 kHz, transmits time signals consisting of 1-second time ticks that are amplitude modulated on the carrier. This signal can be received at long distances and can be used as a time reference to an accuracy in the order of about 0.5 millisecond.

2. VLF Transmissions

A number of radio stations broadcast time signals in the VLF and LF bands. Of these signals the most useful in terms of coverage and propagation stability are those in the VLF region. The available stations and their characteristics are summarized in table 2.

NBA, the best controlled and most useful of these VLF stations, has the following coordinates:

9°	3'	15"	N. Latitude
79°	38'	53"	W. Longitude.

NBA transmits a 1-second pulse whose time of transmission is controlled by the U.S. Naval Observatory. The carrier frequency of 24 kHz is precisely controlled by an atomic standard, from which the timing of the second's pulse is also derived.

The 1-second tick is amplitude modulated on the carrier. The accuracy to which time can be measured depends in part on the pulse rise-time, which is limited principally by the Q of the transmitting antennas. This Q, which is in the order of 500, produces a pulse rise-time of approximately 10 milliseconds.

Close to the transmitter, using a receiver carefully designed to have a wide rf bandwidth and calibrated delay, it is possible to measure time to 1 percent of the pulse rise-time, or to approximately 100 microseconds. However, when making time measurements at greater distances from NBA, several other factors that increase the error are introduced. The receiver used must necessarily have a narrow bandwidth. This further slows the rise of the pulse, particularly at its start, thus making it more difficult to determine the time at which the pulse commences. Stone (ref. 115) demonstrated a consistency of pulse matching in the order of 100 microseconds by observing NBA at NRL in Washington, D.C., but he gives no evidence that the actual start of the pulse was being identified.

Since the shape (and thus the timing) of the transmitted pulse depends upon the Q of the NBA transmitting antenna system, some unpredictable timing changes will occur with varying weather conditions as the conductivity of the antenna ground system changes. There is no evidence of any attempt to control or compensate for such changes.

Actual propagation delays of the time pulse depend upon both the phase- and the group-propagation velocities as related to the theoretical waveguide mode of VLF propagation. Theoretical analyses have been made using simplifying assumptions about the smoothness and reflection coefficient of earth and ionosphere.

TABLE 2. CHARACTERISTICS OF AVAILABLE STATIONS IN LF AND VLF BANDS

Call Sign	Place	Latitude Longitude	Carrier Freq. & Power*	Operating Schedule	Modulation, Time Signals
WWVB	Ft. Collins, Colo., USA	40°40'28.3"N 105°02'39.5"W	60 kHz (H)	Continuous, except that on Tuesdays, WWVB and WWVL shut down for maintenance (at alternate times). Note: WWVL is an experimental station. For details of its current operation write NBS F&T B'cast Services, Boulder, Colorado, 80301.	Identification is a 45° phase advance at 10 min after the hour for a 5 min duration. Seconds are marked by a 10 dB drop in power level. Time information is presented in binary-coded-decimal notation; day of year, hour, minute, and millisecond difference from UT_2 (see Paragraph 2-C for details).
WWVL	Ft. Collins, Colo., USA	40°41'51.3"N 105°03'00.0"W	20 kHz (M)		Call sign at min 00 20 40 each hr.
GBR	Rugby, England	55°22'N 1°11'W	16 kHz	Continuous except approx 1300-1430 UT daily	Morse code time signals for 5 min preceding 0300, 0800, 1500, and 2300 UT.
MSF	Rugby, England	55°22'N 1°11'W	60 kHz (M)	Daily, one hr., 1429-1530 UT (continuous operation is under consideration).	Tick is 5 ms of 1000 Hz, minute mark is 1000 ms (Note: deviations from nominal frequency for GBR, MSF, and Droitwich are published monthly in "The Radio and Electronics Engineer").

*L <1 kW, M 1-5 kW, H >5 kW

TABLE 2. CHARACTERISTICS OF AVAILABLE STATIONS IN LF AND VLF BANDS (Cont.)

Call Sign	Place	Latitude Longitude	Carrier Freq. & Power*	Operating Schedule	Modulation, Time Signals
BBC	Droitwich, England	52°18'N 2°06'W	200 kHz (H)	Continuous (18-20 hours)	
DCF-77	Mainflingen, F.R. of Germany	50°01'N 09°00'E	77.5 kHz (H)	6 days a week: 0645-1035 and 1900-0010 UT (1 Nov-28 Feb) 1900-0210 UT (1 Mar - 31 Oct).	Varied program of time signals, etc., originating alternately from Physikalisch-Technischen Bundesanstalt (PTB) and Deutschen Hydrographischen Instituts (DHI). For example, A1 telegraphy time signals from PTB 0728-0735, 1028-1035, etc. and during min 57 to 59 each hour. Time signals from DHI 0700-0710, 1000-1010, etc. and during min 00-10 ea hr. Carrier with pulses every 2 min from PTB 0645 to 0659, etc. Morse Code call letters. Adjustment, 50 ms steps.
NBA	Balboa, Canal Zone, USA	09°4'N 79°39'W	24 kHz (M)	Continuous	1-second time tick

*L < 1 kW, M 1-5 kW, H > 5 kW

TABLE 2. CHARACTERISTICS OF AVAILABLE STATIONS IN LF AND VLF BANDS (Cont.)

Call Sign	Place	Latitude Longitude	Carrier Freq. & Power*	Operating Schedule	Modulation, Time Signals
NPM	Lualualei, Hawaii, USA	$21^{\circ}26'$N $158^{\circ}09'$W	19.8 kHz (M)	Maintenance 1400 -1900 each Tues.	CW beginning 1/2 hr after odd hours UT. Frequency shift keying beginning odd hours for 30 min.
NSS	Annapolis Md., USA	$38^{\circ}59'$N $76^{\circ}28'$W	21.4 kHz (H)	Maintenance as required.	Time signals, minutes 55-60 each hour.
NLK/ NPG	Jim Creek, Wash., USA	$48^{\circ}06'$N $122^{\circ}16'$W	18.6 kHz (H)	Maintenance 1600 -2400 UT Thurs.	40-44 min, one 200 ms pulse each 2 sec. 44-47 min, key down 47-50 min, key up
NAA	Cutler, Maine, USA	$44^{\circ}38'$N $66^{\circ}17'$W	17.8 kHz (H)	Maintenance as required.	CW beginning odd hours UT. Frequency shift keying beginning even hours UT.
ZUO	Johannesburg, Rep. of S. Africa	$26^{\circ}11'$S	100 kHz (L)	Continuous	
RWM-RES	Moscow, USSR	$55^{\circ}45'$N $37^{\circ}33'$E	100 kHz (H)	Continuous (21 hours per day).	Time signal 40 min in each 120.

*L < 1 kW, M 1-5 kW, H > 5 kW

TABLE 2. CHARACTERISTICS OF AVAILABLE STATIONS IN LF AND VLF BANDS (Cont.)

Call Sign	Place	Latitude Longitude	Carrier Freq. & Power*	Operating Schedule	Modulation, Time Signals
OMA	Podebrady, Czecho.	$50^{\circ}08'$N $15^{\circ}08'$E	50 kHz (M)	Continuous	A-1 telegraphy signals. Call sign in Morse. Step adjustment.
HBG	Prangins, Switzerland	$46^{\circ}24'$N $06^{\circ}15'$E	75 kHz	Continuous	Time signals, 100 msec pulsed carrier marks sec, prolonged for sec 00. Note: to begin operation in fall 1965.

*L < 1 kW, M 1-5 kW, H > 5 kW

During January and February of 1965 ITT Federal Labs (ref. 55) carried out an experiment that was intended to demonstrate equipment which could provide accurate time synchronization using pulses from NBA.

The data collected and reported in this experiment confirm the expectation that timing of the envelope of the NBA 1-second tick, after propagating for some distance, can be measured only to an accuracy in the order of 500 microseconds. ITT privately expressed its expectation of resuming the experiment, which was curtailed when NBA shut down for extensive overhaul in February 1965.

It appears, however, that the shape of the pulse, under the influence of changing propagation conditions, will remain variable. Thus it will be impossible to obtain a timing accuracy of much better than 500 microseconds from NBA over extended periods of time.

C. TWO-FREQUENCY TRANSMISSION EXPERIMENTS AT WWVL

A number of experiments have been performed (refs. 25 and 83) using 20.0 kHz signals from WWVL in conjunction with phase-locked transmissions on 19.9 kHz or 20.5 kHz in order to obtain a time mark that will be unambiguous, even in the VLF band. To date, the experiments have proved the basic stability of the 20 kHz signal to be very good; however, it has not yet been clearly demonstrated that unambiguous time can be devised from a combination of two frequencies.

The technique used in these investigations is to generate the two frequencies (20.0 and 19.9 kHz) so that their sinewaves pass through zero simultaneously in the transmitter at some specific time; they will do so every 10 milliseconds. This "10-millisecond time mark," which is radiated from WWVL, arrives at a receiver some time later - depending upon the particular distance, time of day, season and propagation path. The two frequencies, differing by only 0.5 percent, experience the effects of very similar propagation conditions and, therefore, both take very nearly the same time to traverse the propagation path.

The total phase error due to all causes must be less than ±0.125 microsecond to obtain proper cycle selection at the receiver. Phase errors of from 0.125 to 0.375 microsecond cause 50-microsecond time errors. From 0.375 to 0.625 microsecond, the error is 100 microseconds. Much of the data collected so far shows random errors of this magnitude. Moreover, if the effective velocity of the two waves differs measurably, the wrong cycle might be selected all the time - in the absence of other errors. This choice can only be determined positively by a carefully controlled experiment in which a portable clock is carried from transmitter to receiver.

D. CLOCK SYNCHRONIZATION BY OMEGA

1. Introduction

The following description of the OMEGA system and its utilization for time synchronization projects into the future when a complete world-wide system may be in operation. With reference to clock synchronization accuracy, the discussion also projects into the future when absolute travel time of VLF signals from transmitter to receiver may be predicted to accuracies of 1 microsecond. As of this date (1966), neither of these goals is an accomplished fact. Four experimental OMEGA stations are currently in operation, on an experimental basis, and the best predictions of VLF propagation are in the order of 5 to 10 microseconds (refs. 23, 86, 96, 116 and 120).

OMEGA is a world-wide radio locating system in which eight VLF (10 to 14 kHz) transmitting stations, distributed uniformly around the world, transmit signals that combine to provide a stationary radio-signal field within which the position of a suitable receiver can be determined to within a mile or so anywhere on earth.

The mean phase of the OMEGA signals - when corrected for propagation effects and diurnal variations - provides a universally available, time-scale function of microsecond accuracy from which synchronization of clocks to within 1 microsecond can be obtained anywhere on earth.

2. OMEGA Navigation System

The world-wide, radio-locating signal field is established by transmitting a 1-second segment of a 10.2-kHz cw carrier from each of eight stations, in turn. This transmission sequence is repeated every 10 seconds, with all eight transmission segments synchronized to a common time base in which the relative phase of the signals from each pair of stations provides an independent stationary pattern of iso-phase contours. The location of an observer is given by the intersection of the contours corresponding to the relative phase of any two or more pairs of signals observed at his location.

At least five of the eight stations can be received at any point on earth, thereby providing a redundant choice of contour patterns from which a geometrically strong fix can always be obtained.

To obtain a position with OMEGA, a receiver segregates the signals of at least two pairs of stations and determines their relative phase - while ignoring unwanted and possibly stronger signal components of the same frequencies from the other stations.

This determination is accomplished by providing a commutating function, matching the sequence of signal transmissions, which opens the receiver inputs to the desired signal components and blocks unwanted signals. The receiver also contains phase measuring circuits for determining the relative phase of signal components that do not occur at the same time.

Position information so obtained is, however, ambiguous since the signal phase of each pair of stations, being naturally periodic, defines a family or grid of more-or-less parallel iso-phase contours with a minimum spacing of one-half wavelength (approximately eight miles) - only one contour of which contains the observer.

Resolution of the ambiguity is provided by having each station transmit additional signal components at related frequencies in other segments of the signal sequence: viz, at 13.6 kHz (4/3 of 10.2 kHz) in the segment following the 10.2-kHz signal, and at 11-1/3 kHz (10/9 of 10.2 kHz) in the succeeding segment. These additional signal components are likewise synchronized to the common time base.

The iso-phase contour patterns corresponding to all three frequencies (10.2, 11-1/3, 13.6 kHz), when overlaid, form a Moire pattern identifying every ninth contour of the 10.2-kHz pattern, thus widening the ambiguity to 72 miles.

Further reduction of the ambiguity is provided by narrowband phase modulating the 13.6-, 11-1/3- and 10.2-kHz components transmitted from each station with 226-2/3 Hz (1/45 of 10.2 kHz), 45-1/3 Hz (1/225 of 10.2 kHz), and 11-1/3 Hz (1/900 of 10.2 kHz), respectively. The complete pattern widens the unambiguous band, theoretically, to some 7200 nautical miles.

In radiating the commutated signal format, each station transmits for 3 to 4 seconds in each 10-second period. An alternate mode of operation, permitting signal separation by frequency-domain filtering rather than by time multiplex, is provided by having each station transmit a submultiple of 408 kHz - likewise synchronized with the common system time base - during the remaining 6 to 7 seconds of each sequence when it otherwise would be silent. These "side frequency" components are distinct from the commutated signal format, and each station transmits a different submultiple of 408 kHz as its side frequency so that each side frequency has a clear channel.

The side frequencies, being submultiples of a common higher frequency, provide an alternate stationary phase pattern from which position can be determined. Since each signal has a clear channel, the side frequency signals of the different stations can be separated by simple tuned filters; no time multiplex synchronization and switching is required. However, the ambiguity of the phase contour pattern is that of the common multiple frequency, approximately 1200 feet. This lane width is essentially unresolvable; thus the side frequency pattern is primarily useful for keeping track of position with respect to a known point of departure, with continuous tracking of the signals.

3. OMEGA Signal Format

One period of the over-all OMEGA signal format is illustrated in figure 21 as it might appear at some point on earth. The first three lines show the commutated phase-modulated signals at 10.2, 13.6, and 11-1/3 kHz, respectively; and the remaining eight lines show the side frequency transmissions of the individual stations. In this format Station A, for example, transmits a 10.2-kHz signal phase modulated with 11-1/3 Hz in the first (0.9 sec) segment of the sequence, the station next switches to 13.6 kHz phase modulated with 226-2/3 Hz in the second (1/0 sec) segment, and then switches to 11-1/3 kHz modulated with 45-1/3 Hz in the third (1.1 sec) segment. During the remaining five segments of the sequence, Station A transmits a cw signal at 12.363 kHz (equal to 408/33).

Station B transmits a similar sequence, starting with the second segment and transmitting a side frequency of 12.000 kHz (equal to 408/34). Stations C through H follow in turn, transmitting the commutated frequencies and the individual side frequencies as shown in figure 21.

To provide switching time and to allow for differences in transmission time from stations at different distances, the commutated signals have a nominal gap of 0.2 second between transmissions so that nowhere do the signals of the same frequency from different stations overlap in time.

The entire sequence (including the gaps) is exactly 10 seconds long, and the length coding (see paragraph V.D.3.a.) is designed so that the first and last four segments (also including the gaps) occupy exactly 5 seconds each.

To provide a clear indication of time, gaps of 0.2 second are inserted in the side frequency transmissions on the minute and each 5 seconds of Universal Time. These gaps correspond to the zero and 5-second gaps of the commutated sequence so that all transmissions are interrupted for 0.2 second at every 5-second epoch.

a. Signal Identification

The transmissions of a particular station in the commutated sequence can be identified by any one of several different more-or-less independent methods.

At any given location a rudimentary estimate of relative station distances will indicate which station(s) provide the strongest signals, thereby permitting the sequence phase to be identified by visual recognition of the commutated signal amplitudes in an oscilloscope pattern. Likewise, the transmission of each side frequency ceases when the corresponding station is transmitting its three segments of the commutated pattern. Since each side frequency has a clear channel, a signal indicating the phase of the commutating sequence can be obtained with a simple variable filter tuned to any one of the side frequencies.

The commutating sequence will be timed so that each sequence starts on an exact 10-second epoch of Universal Time in order that the transmissions of a particular station can be identified by reference to a chronometer or other time scale reading to approximately 1 second.

Finally, to provide for automatic identification of the signals of a particular station, the transmissions are length-coded; that is, the successive transmissions by the different stations instead of being of equal length vary in length from segment to segment of the sequence in accordance with the following regular pattern:

Segment Designation	Length of Transmission (Seconds)
A	0.9
B	1.0
C	1.1
D	1.2
E	1.1
F	0.9
G	1.2
H	1.0

Recognition of the lengths of any two transmissions defines the phase of the pattern or sequence, while the transmissions of a particular station are identified by their occurrence within the sequence.

In an automatic receiver a 10-second correlating function can be generated (refer to Appendix II) which, upon being cross correlated with the signal envelopes, goes to a maximum when in alignment. A commutating function in the correct phase with respect to the correlating function will then segregate the signals of the different stations.

b. OMEGA Signal Timing Epochs

The complete OMEGA signal format, as transmitted from each station, consists of a repeating 10-second sequence comprised of 1-second transmissions at 10.2, 13.6, and 11-1/3 kHz, in turn, which are phase modulated with 11-1/3, 226-2/3, and 45-1/3 Hz, respectively. This portion is followed by the transmission of a cw signal at some submultiple of 408 kHz for the remaining 6 to 7 seconds of each 10-second period.

With the exception of the side frequency component, the sinusoidal components of the signal are all exact harmonics of the lowest (11-1/3 Hz) frequency component and are specified to have coincident zeros at this lowest frequency - i.e., the amplitudes of all six components pass through zero with positive slope, concurrently, every 3/34-second.

The lowest sinusoidal frequency component (11-1/3 Hz) traverses exactly 34 periods in 3 seconds (11-1/3 equals 34/3). This component is controlled in phase so that its amplitude passes through zero with positive slope at the start of a 10-second commutating sequence period. This coincidence is repeated three sequences (30 seconds) later and every 30 seconds thereafter. At the intervening 10-second epochs, it either leads or lags by one-third period.

Thus, the multiple coincidence of positive-going zero's of the sinusoidal components with the start of a multiplex sequence defines a sequence of timing epochs or time scales with 30-second intervals which, when referred to the phase of the rf components, can be read to a fraction of a microsecond. The overall timing of the OMEGA system is to be adjusted so that each of these timing epochs, as transmitted from all stations, coincides with the 30-second epochs of UT2 or another accepted time scale.

4. Station Timing

In order for the system to provide a stationary phase field by which position can be determined, it is essential that the signals of all eight stations be fixed in phase with respect to a common time base. This relationship is established first by providing each station with an extremely stable and reliable timing system and then by controlling the phase of the emitted signal with respect to this stable internal time scale. This way the deviation in phase of the emitted signal is minimized from the mean of all signals (i.e., the system mean) and the system timing, as transmitted, is steered to maintain a fixed phase with respect to Universal Time.

Each station is to be provided with four atomic frequency standards, giving a total of 32 in the system. At each station the output of its four standards are interconnected so as to provide a time base that is the concensus of the four. The signal waveforms to be transmitted are then derived from the mean time base by quadruply-redundant frequency synthesizers and associated circuitry so interconnected that the probability of loss of phase continuity within a station is negligible.

At each station the phase of each of the signals received from all other stations within range is to be determined with respect to the local time scale and, after correction for predicted travel time between stations, reduced mathematically to give the deviation of the phase of the particular station signals from the mean of the system.

At intervals the phase of each station is then to be corrected, according to a weighted synthesis of its deviations from the system mean, so as to minimize the deviations. Because of the extreme stability of the time base at each station, the corrections will always be small (i.e., in the order of 1 microsecond or so, at the very most) and are made at intervals of 24 hours or more. This represents a long time integration and smoothing of the apparent deviations over several days, which substantially eliminates all variations caused by diurnal changes in propagation time, other short-term propagation disturbances, and noise.

The mean phase of the system is thus to be determined by the concensus of 32 atomic standards and is expected, ultimately, to have a primary frequency stability - exclusive of phase corrections introduced to steer the system to Universal Time - of approximately $1{:}10^{14}$.

Each station is expected to maintain the phase of its transmissions fixed with respect to the system mean to within less than 1 microsecond. In addition, the phase of the signals, as observed at each station, are reported to an OMEGA system control center. The control center - having available data from both ends of all baselines - is expected to be in a position to justify the predictions of travel times around the system and to develop corrected values of the predictions of time of travel so as to eliminate long-term discrepancies in the signal timing.

The control center or some other authority will also compare the phase of the OMEGA signal pattern with the Universal Time signals from recognized sources (WWV, et al) and/or established astronomical observations, and develops system steering information which, when added to the phase corrections at each station, maintains the mean system phase synchronous with Universal Time.

After a sufficient period of operation (several months, or a year or more of the full net of eight stations), it is expected that the predictions of travel time between stations may be refined to the point that the absolute deviation of any one station from the system mean will not exceed 1 microsecond.

5. Time Signal Receiver

To establish time synchronization with the OMEGA signal, it is necessary to have a stable, local time-scale source as well as a means for indicating the OMEGA signal's phase in order to determine the phase of the local time scale with respect to the OMEGA signal.

a. Signal Phase Determination

The phase of the OMEGA signal is determined in two major steps: First, a multiplex switching function is synchronized to the OMEGA signal segment envelopes in order to segregate the signals of a particular station or several stations. Then the relative phase of the sinusoidal components for the signals from the selected station(s) is determined, thereby establishing the 30-second timing epochs and determining their relative timing with an accuracy of approximately 1 microsecond.

b. Identification of Multiplex Sequence Phase

The leading edge of each transmission builds up in approximately 100 milliseconds along a transient waveform determined by the transmitter excitation and power, and by the transmission characteristics of the antenna and coupling network. The start of each transmission is timed in such a manner that a linear extrapolation of the straight portion of the leading edge to zero (figure 22) intersects the axis at a fixed phase with respect to Universal Time.

The extrapolation to zero can be accomplished with an accuracy in the order of 10 percent of the leading edge of the transmission. Thus the beginning of each commutated signal segment and the beginning of each side frequency transmission delineates a 10-second epoch of UT to within about 10 milliseconds in accordance with the schedule given in table 3.

TABLE 3. PROJECTED SCHEDULE FOR 10-SECOND EPOCH OF UNIVERSAL TIME

Time (Seconds)	Frequency (kHz)	Station	Location*
10N + 0	12.750	F	Not established
10N + 1.100	10.462	G	Not established
10N + 2.300	11.657	H	Not established
10N + 3.400	12.363	A	Norway
10N + 5.000	12.000	B	Trinidad, W.I.
10N + 6.300	10.737	C	Hawaii
10N + 7.400	13.161	D	Forestport, N.Y.
10N + 8.800	11.027	E	Not established

*Refer to table 4 for station coordinates.

6. Summary of Timing Receiver Operation

The OMEGA timing signal receiver consists of

- A local time standard generating a set of reference waves that match the format of the OMEGA signals
- A set of multiplex switching waveforms for segregating the signals from the different stations

- Correlating waveforms for indicating alignment between the local multiplex function and the received signal multiplex sequence
- A set of tracking filters filtering and amplifying the received signals
- A ganged phase shifter
- A phase correlator and phase servo for adjusting the shifted reference waves to match the signals as received.

Cross-correlating the correlating waveforms with the signal envelopes indicates to within about 10 milliseconds the state of the alignment of the local timer with the OMEGA signal sequence.

The phase correlator then adjusts the phase shifter to match the local reference waves to the received signals. The setting of the phase shifter then indicates the phase difference between the local timer and the received signals with an accuracy of a fraction of a microsecond, and with no ambiguity.

The absolute phase of the timer can be adjusted so that the phase indication is the negative of the predicted retardation and diurnal variation for the given location. The timer thereby matches the mean phase of the OMEGA signals as transmitted (i.e., Universal Time) with an accuracy which depends on the accuracy of prediction - ultimately becoming approximately ± 1 microsecond.

A detailed description of an OMEGA timing receiver designed specifically for this application is contained in Appendix II.

7. Survey Errors

The objective of conducting a precise survey of transmitter and receiver locations is to render the error in prediction of signal transmission time less than that of the other error sources. For OMEGA this means less than 1 microsecond, or approximately 1000 ft. The location of the transmitters is assumed to be very accurately known; but over long distances, the discrepancies between the local datum and that used to locate the transmitter positions can produce errors of a magnitude which may be 1000 feet or more. These problems are in the process of being resolved by agencies such as the U.S. Navy Oceanographic Office and the USAF. Some of the results are security classified at present, so that it is not possible to assign any generalized value stating the accuracy to which any arbitrary long path can be determined.

At the rate the various programs are progressing, however, it is reasonable to expect that survey accuracies will be improved before the OMEGA system becomes fully operational.

It is also feasible to use an OMEGA receiver to determine position in the OMEGA grid, then to calculate the distance to the stations, and obtain the travel time - thus eliminating the survey error as a factor in time synchronization.

8. Status of System

At present, four stations (refer to table 4) of the proposed eight station OMEGA network are in operation on an experimental basis, providing signals over a wide area which can be used for navigation and for timing. There are no production navigation receivers available at present and no receivers have been built which are designed specifically for timing.

When (and if) the system becomes operational and receivers are available (which cannot take place before 1968), OMEGA may be the most convenient method of distributing Universal Time to microsecond accuracy.

TABLE 4. GEOGRAPHIC COORDINATES OF OMEGA STATIONS

Station Designation	Station Site	Station Latitude and Longitude
A	Aldra, Norway	66° 25' 15" N Lat 13° 09' 10" E Long
B	Trinidad, W.I.	10° 42' 06" N Lat 61° 38' 20" W Long
C	Haiku, Hawaii	21° 24' 29" N Lat 157° 50' 01" W Long
D	Forestport, N.Y.	43° 26' 42" N Lat 75° 05' 10" W Long

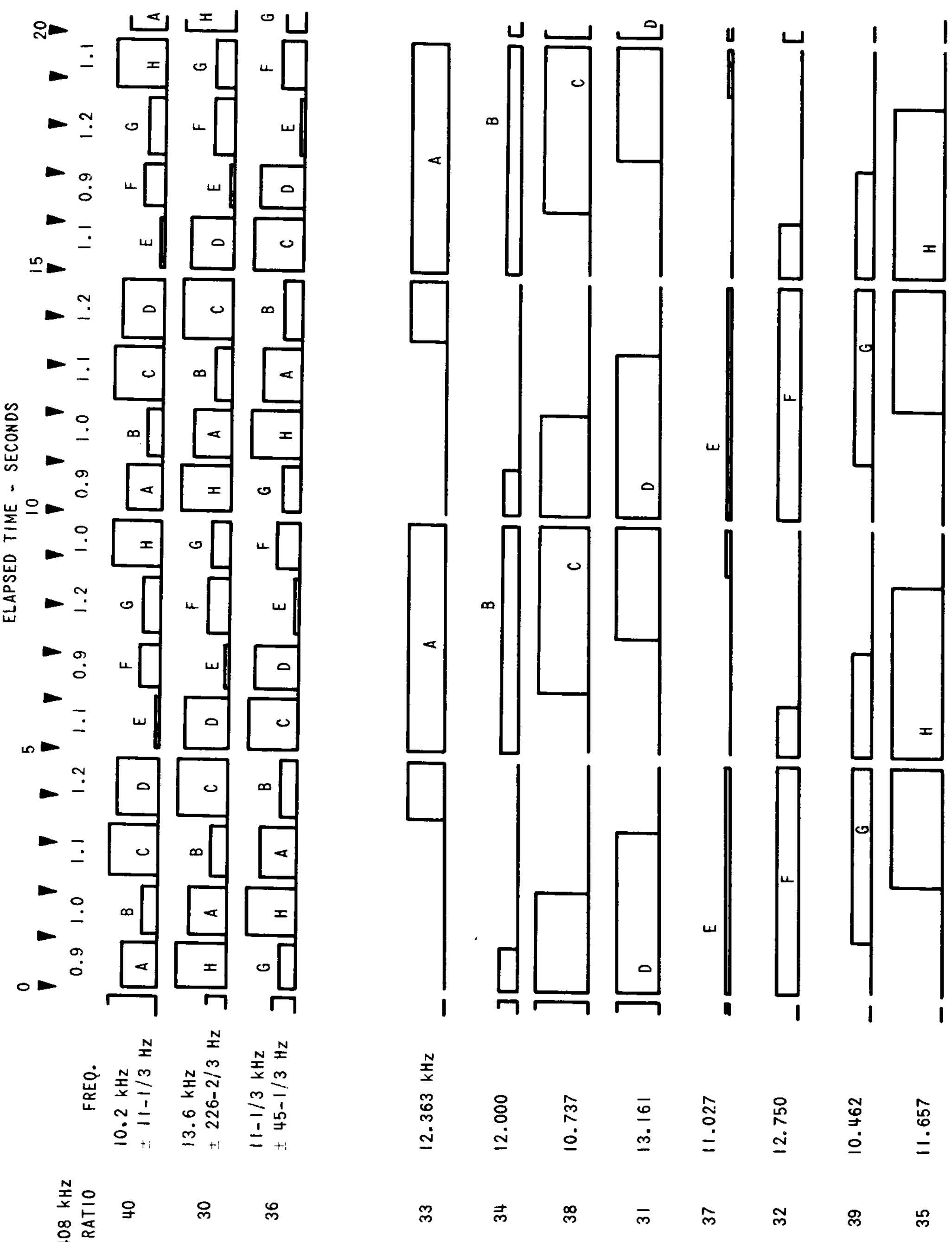


FIGURE 21. OMEGA SIGNAL FORMAT, TIMING DIAGRAM

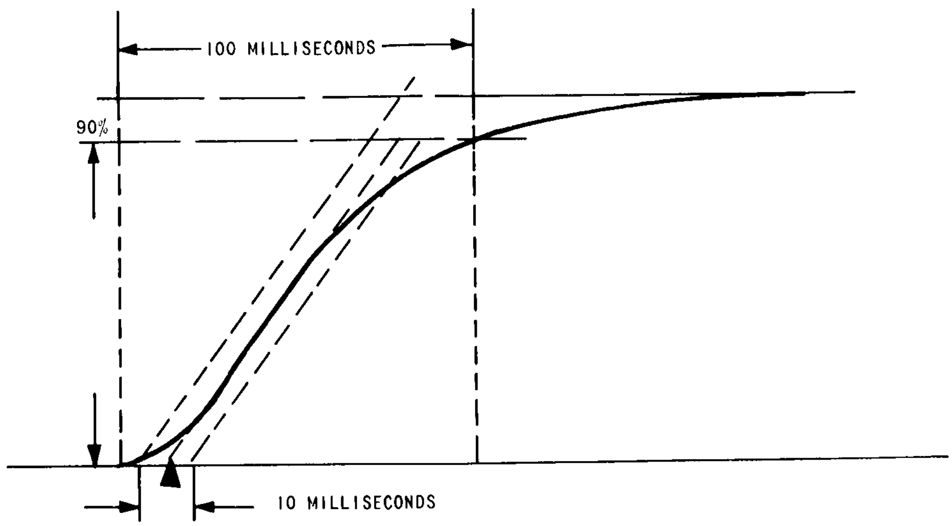


FIGURE 22. PLOT SHOWING EXTRAPOLATION OF LEADING EDGE OF OMEGA SIGNAL

SECTION VI

LOW-FREQUENCY CLOCK SYNCHRONIZATION SYSTEMS

A. INTRODUCTION

The LF band (30 to 300 kHz) contains a number of facilities which can be used for clock synchronization. Standard time signals of various types are transmitted by the stations listed in table 2. Of these signals, WWVB transmits atomic seconds, adjusted to be within 100 milliseconds of UT 2 time. WWVB broadcasts, in code, the departure between its second and the UT2 second (refer to Section 2).

The Loran-C Navigation System provides pulse signals on 100 kHz which can be used for time synchronization of clocks to a fraction of a microsecond over specific areas of 1000 to 2000 miles radius. The chain on the east coast of the U.S. (SLO) is synchronized to Universal Time by the U.S. Naval Observatory. (This is the only Loran-C area that provides synchronization to UTC.) The synchronization areas can be increased to a radius of approximately 4000 miles by use of nighttime skywave propagation, but only to an accuracy of 15 to 30 microseconds.

The propagation characteristics of LF signals provide wide area coverage for these systems, as detailed in the following discussion.

B. LORAN-C SYNCHRONIZATION

1. Functional Description

Loran-C - a pulsed-hyperbolic radio navigation system operating at 100-kHz - is used for precision navigation purposes on both ships and aircraft (ref. 45). A Loran-C chain, of which seven are now operating in various parts of the northern hemisphere (see tables 5 through 11), consists of a Master transmitting station and two or more Slave stations, each transmitting groups of eight pulses alternately on a common time base. The transmissions of the Master station are followed, after a fixed "coding delay" by each of the Slave stations, in turn. Each chain operates on a different repetition rate in order to avoid mutual interference between chains. A typical Loran-C pulse repetition interval is illustrated in figure 23, which also includes an expanded portion showing the master pulse pattern and the envelope shape of a typical transmitted pulse.

A receiver operating in a region where it can receive the Master station and two Slaves measures the time-of-arrival and phase of the received 100-kHz pulses. The receiver determines its position by the observed time and phase difference. Navigation receivers use synchronous detection to improve performance in noise. They also employ special circuits that automatically synchronize the receiver on a particular rf cycle on the leading edge of the received pulses. This procedure is necessary to assure that corresponding portions of only groundwave signals are being compared.

This two-step "envelope" measurement and "cycle" measurement is an essential element of the Loran-C technique. The receiver measures the time delay between the Master and Slave pulses, and also measures the phase of the 100-kHz carrier of the pulses relative to one another. Phase measurement accuracy in the order of 1 degree, or 0.03 microsecond, is obtainable. Analog type receivers use calibrated 100-kHz phase shifting resolvers, while newer digital receivers measure time delay and phase difference directly, using digital counters.

2. Use for Clock Synchronization

Since all the stations in a given Loran-C chain transmit with a known, fixed time relationship to the rest of the stations, a receiver that can measure the time-of-arrival of the signal from one station can set a clock relative to the Loran-C chain provided it also knows

- The relative transmission time of the Loran-C station
- The propagation time of the signal from the station to receiver
- Absolute time delays in the receiver.

Relative clock synchronization to accuracies in the order of tenths of a microsecond can be obtained within any of seven areas in the northern hemisphere by use of groundwave signals from Loran-C. Each area, extending 1000 to 1500 miles from each station (see figure 24) is roughly circular and 3000 to 5000 nm in diameter. An additional chain, not shown, is scheduled to be installed in southeast Asia about 1 September 1966.

A much greater range (3000 to 4000 miles from each station) can be obtained via skywave propagation at night, but the accuracy obtainable is only in the order of 15 to 30 microseconds (refs. 1 and 40).

All chains use rubidium-vapor frequency standards at the master station to insure excellent frequency stability. Only one Loran-C chain - located on the east coast of the U.S. with its master station at Cape Fear, N. C. and operating on a repetition rate of 12-1/2 groups per second - has its transmissions related to Universal Time. The transmissions from Cape Fear are monitored by the U.S. Naval Observatory and the necessary adjustments are made to keep the transmissions synchronized to UTC (ref. 123).

The Cape Fear Master Station transmits an additional pulse at a 1-second rate, held to UTC to better than 20 microseconds. None of the other six chains are synchronized to world time or to each other. Such synchronization is feasible, but has not been implemented - partly because no urgent need has been indicated.

a. Clock Synchronization Error Budget

The overall clock-synchronization error is a function of the following parameters:

- Transmitting system errors
- Survey errors
- Propagation errors
- Receiving system errors
- Clock errors.

These will now be discussed and evaluated in turn. Numerical examples are given in the error analysis summaries of tables 12 and 13 at the end of this section.

(1) Transmitting System Errors. This type of error results from instabilities in the Master station signal and variations in the "coding delay" of the Slave stations relative to the Master. With the recent installation of high-precision, rubidium-vapor frequency standards at all Master stations, the instabilities of the Master signal can be considered negligible. The synchronization error of the Slave stations depends on Master transmitter power, baseline length, noise and interference levels, and on the skill and dilligence of the operating personnel.

Each Loran-C chain has a fixed monitor, located near the center of the service area, whose duty it is to continuously record the synchronization of the chain. In addition, the Master station monitors the synchronization of each Slave. Either the Master or the area monitor has the responsibility to order changes in Slave station-coding delay to maintain the synchronization of each chain within specified limits, usually ±0.1 microsecond. Actual performance varies from time to time and from chain to chain, with some chains held to 0.05 microsecond. A value of 0.1 microsecond for Slave station synchronization may be taken as representative of the present performance of the chains (refs. 36, 37, 41, and 42).

(2) Survey Errors. The techniques for computing the great circle distance between two points whose latitude and longitude are known are treated adequately elsewhere and will not be discussed further here. A basic source of error in this computation is that of inaccuracies in the precise geographic locations of the transmitter and receiver. It is assumed that the receiver location

will be surveyed with respect to local and international datum, to an accuracy commensurate with the accuracy of timing to be required.

The exact location of all the Loran-C transmitting stations has been determined by the Navy Oceanographic Office to 0.1 second of latitude and longitude relative to the Mercury datum.

Tables 5 through 11 give data on all the Loran-C chains, with their geographic positions given to the accuracy available. The exact position of some stations located in foreign countries has not yet been released because clearance from the host nation has not yet been obtained.

The position information can now be used for calculating propagation time. An error of 100 ft in location, in an unknown direction, causes a probable error of 64 ft in distance to the receiver, which produces a probable timing error of 0.065 microsecond.

The relative transmission times of the Loran-C stations can be determined by reference to Loran-C Charts such as the VLC-30 series published by the U.S. Naval Oceanographic Office. The timing of each Loran-C Slave station is readily obtained from the Master and Slave baseline extension values, which are given on the charts to within 0.01 microsecond. If E_s is the time difference reading on the Slave baseline extension and E_m is the Master baseline extension reading, then the Slave transmission time (relative to the Master) can be expressed as

$$T_s = 1/2\,(E_m + E_s)$$

In this way the two essential parameters, position and relative transmission time, can be determined for any of the Loran-C stations.

(3) Groundwave Propagation Errors. Analysis of operating data from the U.S. East Coast chain (ref. 37) indicates that it is possible to predict Loran-C, one-way groundwave travel time over seawater to about ±0.1 microsecond for paths up to at least 1000 miles. This includes corrections for atmospheric refraction and secondary phase factor, which is function of earth conductivity and vertical lapse rate of atmospheric permittivity.

The travel time of the groundwave signal is given by

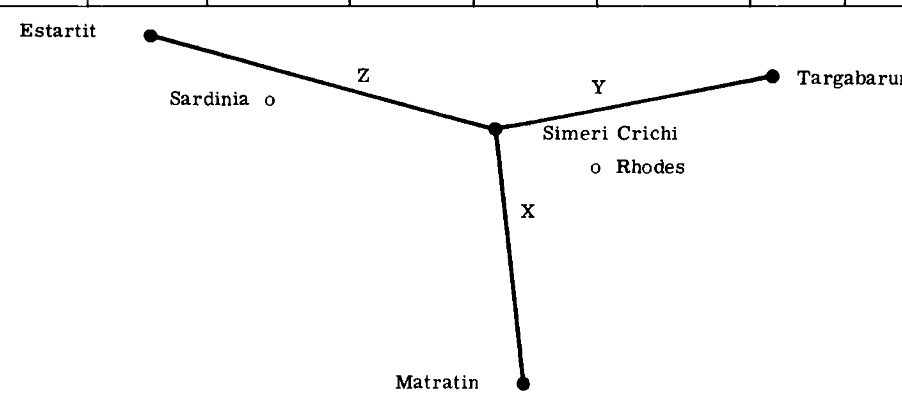
$$T = \frac{D}{c} n + t_c$$

where

D = great circle distance
c = velocity of light
n = index of refraction of medium
t_c = secondary phase factor.

TABLE 5. LORAN-C STATION DATA FOR MEDITERRANEAN CHAIN (SL4), 1 AUGUST 1965

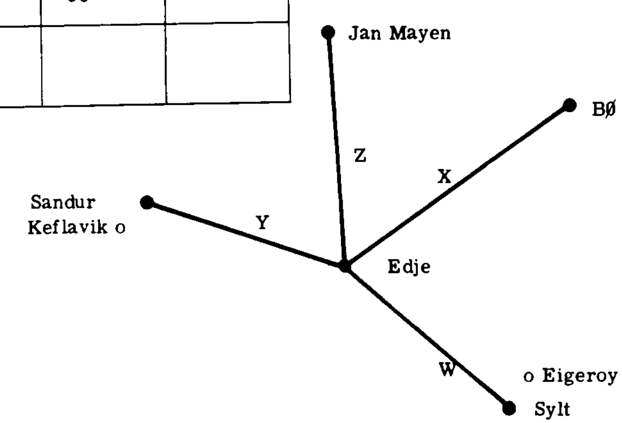
Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
Simeri Crichi, Italy	38-52-16.4N	16-43-05.2E	Master		180KWP AN/FPN-39		AN/FPN-38	AN/URQ-14	625		No	U. S.
Matratin, Libya	30-36N	18-24E	X Slave		180KWP AN/FPN-39		AN/FPN-38	WRS	625	11,000	No	U. S.
Targabarun, Turkey	40-58N	27-52E	Y Slave		180KWP AN/FPN-39		AN/FPN-38	AN/URQ-14	625	29,000	No	U. S.
Estartit, Spain	42-03-39.6N	03-12-23.5E	Z Slave		180KWP AN/FPN-39		AN/FPN-38	AN/URQ-14	625	47,000	No	U. S.
Rhodes, Greece	36-25N	28-10E	Monitor			AN/SPN-30					No	U. S.
Sardinia, Italy	39-11N	09-10E	Monitor			AN/SPN-29					No	U. S.



(SL4) 79,600 μsec

TABLE 6. LORAN-C STATION DATA FOR NORWEGIAN SEA CHAIN (SL3), 1 AUGUST 1965

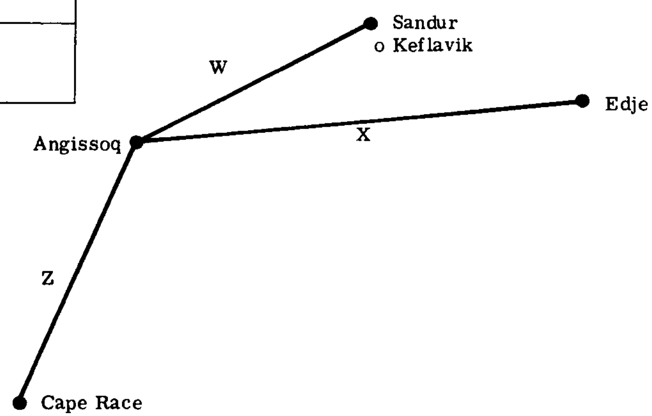
Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
Edje, Faeroes	62-17-56.6N	07-04-14.7W	Master	SL 7 X Slave	AN/FPN-44 (DP) 400KWP		AN/FPN-46	AN/URQ-11	625		No	Danes
Bø. Norway	68-38-01.7N	14-28-02.3E	X Slave		180KWP AN/FPN-39		AN/FPN-38	AN/URQ-14	625	11,000	Yes	Norwegian
Sylt, Germany	54-48-32.8N	08-17-45.7W	W Slave		AN/FPN-42 (MOD.) 240KWP		AN/FPN-41 (MOD)	AN/URQ-11	625	26,000	No	U. S.
Sandur, Iceland	64-54-30.7N	23-55-08.2W	Y Slave	SL 7 Master	3MWP AN/FPN-45 (DP)		AN/FPN-46	AN/URQ-11	1350	46,000	Yes	Icelanders
Jan Mayen Island	70-54-55.9N	08-43-58.6W	Z Slave		180KWP AN/FPN-39		AN/FPN-38	AN/URQ-11	625	60,000	Yes	Norwegian
Eigeroy, Norway	58-27N	05-54E	Monitor			AN/SPN-29					No	Norwegian
Keflavik, Iceland	63-58N	22-34W	Monitor			AN/SPN-30					No	Coast Guard



(SL3) 79,700 μsec

TABLE 7. LORAN-C STATION DATA FOR NORTH ATLANTIC CHAIN (SL7), 1 AUGUST 1965

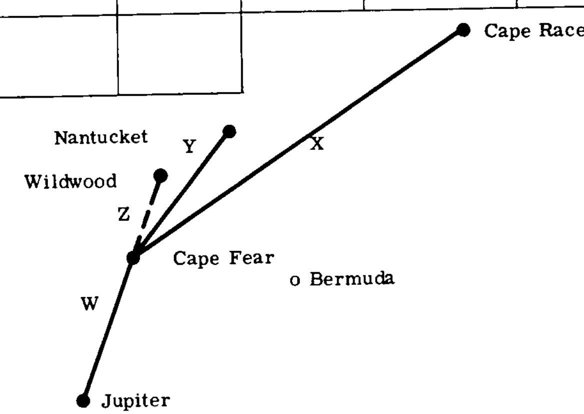
Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
Angissoq, Greenland	59-59-21.5N	45-10-18.9W	Master		1.2MWP AN/FPN-45		AN/FPN-46	AN/URQ-11	625		No	Danes
Sandur, Iceland	64-54-30.7N	23-55-08.2W	W Slave	SL3 Y Slave	3MWP AN/FPN-45 (DP)		AN/FPN-46	AN/URQ-11	1350	11,000	Yes	Icelanders
Edje, Faeroes	62-17-56.6N	07-04-14.7W	X Slave	SL3 Master	AN/FPN-44 (DP) 400KWP		AN/FPN-46	AN/URQ-11	625	21,000	No	Danes
Cape Race, Newfoundland	46-46-32.0N	53-10-28.5W	Z Slave	SLØ X Slave	3MWP AN/FPN-45		AN/FPN-46	AN/URQ-14	1350	43,000	No	Canadians
Keflavik, Iceland	63-58N	22-34W	Monitor			AN/SPN-30					No	U. S.
So. Anthony, Newfoundland	51-30N	55-50W	Monitor			AN/SPN-29					No	Canadians



(SL7) 79,300 μsec

TABLE 8. LORAN-C STATION DATA FOR U.S. EAST COAST CHAIN (SL0), 1 AUGUST 1965

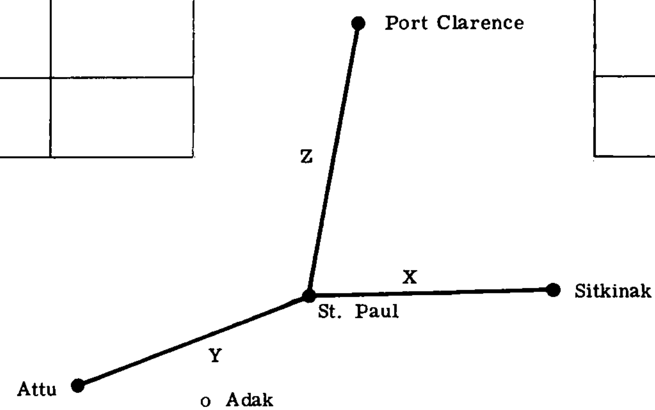
Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
Cape Fear, N. C.	34-03-46.4N	77-54-46.2W	Master		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11 and Rubidium	625		No	U. S.
Jupiter Inlet, Florida	27-01-59.1N	80-06-52.9W	W Slave		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625	11,000	Yes	U. S.
Cape Race, Newfoundland	46-46-32.0N	53-10-28.5W	X Slave	SL 7 Y Slave Z Slave	3MWP AN/FPN-45		AN/FPN-46	AN/URQ-14	1350	26,000	No	Canadians
Nantucket Island, Massachusetts	41-15-11.9N	69-58-38.8W	Y Slave		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625	45,000	Yes	U. S.
EES, Wildwood, N.J.	38-56-58.3N	74-52-01.1W	Z Slave						625	58,000		U.S.
Bermuda Island	32-16N	64-53W	Monitor			AN/FPN-43		AN/URQ-14			No	U. S.



(SL0) 80,000 μsec

TABLE 9. LORAN-C STATION DATA FOR NORTHERN PACIFIC CHAIN (SL2), 1 AUGUST 1965

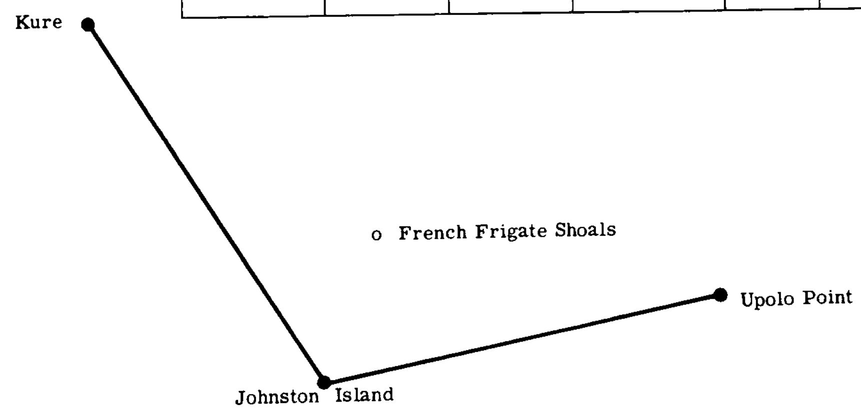
Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
St. Paul, Pribiloff Island	57-09-11.1N	170-14-56.9W	Master		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625		No	U. S.
Sitkinak, Alaska	56-32-21.0N	154-07-43.1W	X Slave		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625	11,000	No	U. S.
Attu, Aleutian Islands	52-49-46.7N	173-10-54.6E	Y Slave		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625	28,000	Yes	U. S.
Port Clarence, Alaska	65-14-41.1N	166-53-10.6W	Z Slave		AN/FPN-42 (MOD) 650KWP		AN/FPN-41	AN/URQ-11	1350	50,000	No	U. S.
Adak, Alaska	52-00N	176-37W	Monitor			AN/SPN-30					Yes	U. S.



(SL2) 79,800 μsec

TABLE 10. LORAN-C STATION DATA FOR CENTRAL PACIFIC CHAIN (SH4), 1 AUGUST 1965

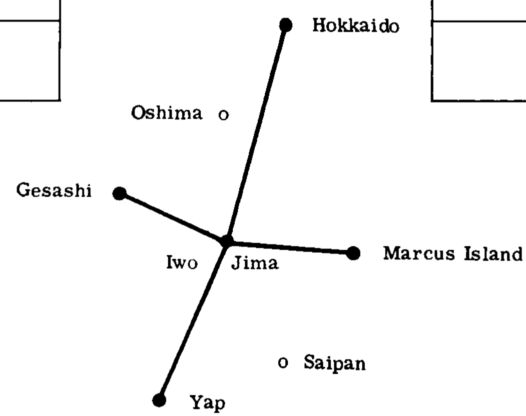
Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
Johnston Island	16-44-47.9N	169-30-28.1W	Master		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625		Yes	U. S.
Upolo Point, Hawaii	20-14-53.9N	155-53-10.7W	X Slave		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-14	625	11,000	Yes	U. S.
Kure Island	28-23-39.2N	178-17-26.3W	Y Slave		240KWP AN/FPN-42		AN/FPN-41	AN/URQ-11	625	30,000	No	U. S.
French Frigate Shoals	23-52N	166-17W	Monitor			AN/SPN-29					Yes	U. S.



(SH4) 59,600 μsec

TABLE 11. LORAN-C STATION DATA FOR NORTHWEST PACIFIC CHAIN (SS3), 1 AUGUST 1965

Station Site	Location		Chain Function		Loran-C Equipment				Remarks			
	Latitude	Longitude	Primary	Secondary	Transmitter	Receiver	Timer	Frequency Standard	Tower (Ft)	Coding Delay (μsec)	Loran-A Capability	Manned By
Iwo Jima	24-47-57.5N	141-19-23.4E	Master		AN/FPN-45 (MOD) 3MWP		AN/FPN-46	AN/URQ-11 and Rubidium	1350		Yes	U. S.
Marcus Island	24-17-07.8N	153-58-44.9E	W Slave		3MWP AN/FPN-45		AN/FPN-46	AN/URQ-11	1350	11,000	No	U. S.
Hokkaido, Japan	42-44-30.4N	143-43-08.7E	X Slave		400KWP AN/FPN-44		AN/FPN-46	AN/URQ-11 and Rubidium	625	30,000	No	U. S.
Gesashi, Okinawa	26-36-24.3N	128-08-57.1E	Y Slave		400KWP AN/FPN-44		AN/FPN-46	AN/URQ-11	625	55,000	Yes	U. S.
Yap Island	09-32-40.0N	138-09-49.8E	Z Slave		AN/FPN-45 (MOD) 2MWP		AN/FPN-46	AN/URQ-14 and Rubidium	1000	75,000	Yes	U. S.
Oshima, Japan	34-41N	139-26E	Monitor			AN/SPN-30					Yes	U. S.
Saipan	15-08N	145-42E	Monitor			AN/SPN-30					Yes	U. S.



(SS3) 99,700 μsec

The great circle distance is calculated from the known geographic positions of transmitter and receiver. The velocity of light is computed to the best accuracy, 299.79250 km/sec, which converts to a value of propagation delay which can be expressed as $1/c = 6.181776$ microseconds per nautical mile. The value of the index of refraction used is that of air, which generally ranges from 1.00030 to 1.00035. Refractivity is usually measured in N units, where

$$N = (n-1)10^6$$

Typical values of N run from 300 to 350. An error of 20N units will introduce an error of 20 parts per million in the travel time. For a 1000-mile path, this error alone will produce a timing error of 0.1 microsecond - which is compensated somewhat by changes in the secondary factor, t_c.

Secondary factor t_c is an artificial correction used to take into account the retardation of the signal caused by the finite conductivity of the earth as well as that from the bending of the rays due to the vertical lapse rate of the permittivity - generally measured in terms of Δ N units per kilometer. The basic relationships derived in NES Circular 573 (ref. 65) have been plotted in figure 25 which shows the variation of the secondary factor, t_c, with distance from the source, where N has a value of 314, for different ground conductivities. Seawater, with a conductivity in the order of 5000, permits prediction of travel time to 0.1 microsecond. On such paths it is possible to make a more accurate computation of travel time by taking N into account. The "standard" travel time is first calculated using a value of 6.181776 microseconds per nautical mile for $1/c$ and obtaining t_c from figure 25. The average value of N along the path must be determined from weather data sources. Reference to figure 26 for the specific value of N allows interpolation of Δt.

For paths over land the conductivity of the earth along the path must be determined in order to calculate the secondary phase factor. Conductivity maps are available for the 48 states, Southern Canada, and Western Europe.[3] For areas where no measurements are available typical values for different types of terrain can be extrapolated from the available data. Obviously, the accuracy of prediction of propagation time depends upon the amount of land in the path and the accuracy to which its conductivity is known. The importance of an accurate determination of earth conductivity , especially in areas of poor conductivity, is illustrated in figure 25. For example, at 1000 miles the secondary phase shift over average earth, where σ equals 5, is more than 2 microseconds less than it would be over poor earth, where σ equals 2. The greater the error in estimating conductivity and the poorer the conductivity, the greater the error in travel time.

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[3] Refer to Sperry drawing No. 4223-96370, prepared from a composite of available conductivity data.

For paths of uniform conductivity, the curves of figure 25 can be used directly to determine secondary factor. For mixed paths, a more complex procedure is required. Using the graph, proceed as shown in figure 27 following the appropriate curve for each portion of the path from transmitter to receiver. Then, in order to maintain reciprocity, repeat the same procedure, reversing the positions of transmitter and receiver. The true secondary factor is the average of the two values obtained. Errors can be reduced to between 0.2 and 0.5 microsecond by careful analysis, but each path is a special case and must be treated accordingly.

In addition, receiver sites close to a discontinuity of earth conductivity, particularly a coastline, are subject to errors of a fraction of a microsecond as a result of the phase-interference pattern set up. Simple cases have been analyzed theoretically by Wait (ref. 129), but no general solution is known.

(4) Receiving System Errors. The receiving system is required to make a time measurement on a particular point on the Loran-C pulse. As transmitted, a Loran-C pulse rises to about 50-percent amplitude in 30 microseconds (3 cycles). The peak is at 80 microseconds and the overall duration approximately 250 microseconds. In order to identify the third cycle, a Loran-C receiver needs an rf bandwidth in the order of 20 kHz, with a rolloff of no more than 18 db per octave (three tuned stages). A narrower passband, or sharper rolloff, results in too slow a rise (or too great a precursor) to permit accurate identification of the third cycle, thereby causing uncertainty in cycle selection and an error of a multiple of 10 microseconds in the timing output.

Random variations in readings due to the presence of atmospheric noise and interference will be encountered at long distances from the transmitters. The signal-to-noise ratio is a function of distance, transmitter power, and noise level. The field strength obtained from Loran-C transmitters is shown in figure 28 as a function of distance and earth conductivity. The atmospheric noise level, which varies widely with location and time, is best described in CCIR Report No. 322, "World Distribution and Characteristics of Atmospheric Radio Noise" (ref. 24).

The distance at which the signal equals the average noise can generally be taken as a practical limit for operation. For example, in 30-db noise an AN/FPN-42 transmitter range over seawater will be approximately 1300 miles (refer to figure 28). At this range the noise error will be approximately 0.1 microsecond.

The absolute delay of the receiver can best be calibrated under test conditions using a Loran-C signal simulator. Any factory test should measure delay as a function of temperature, line voltage, and tolerance of interchangeable components - especially vacuum tubes. An average tolerance of 0.2 microsecond can be expected.

(5) Clock Errors. For a system synchronized to the Loran-C groundwave, a time comparison is made continuously in the case of an automatic tracking receiver, or at frequent intervals where a manually operated receiver is used. Clock errors will accumulate in the manually operated system as the frequency standard (assumed to be a crystal-controlled oscillator) drifts. The clock time error, E, due to oscillator errors is given by

$$E = E_o + \frac{\Delta f}{f} t + \frac{at^2}{2}$$

where

E_o = initial time error

$\frac{\Delta f}{f}$ = fractional frequency error

a = aging rate

t = time.

Values of clock error as a function of $\Delta f/f$ and a for different periods of time can be obtained by reference to figures 17 and 18. For example, with a manually adjusted standard if the frequency is set to one part in 10^{10}, an error of 0.36 microsecond per hour will accumulate. A typical aging rate for a good standard is one part in 10^{10} per day. In 1 hour, this error will be negligible, thus indicating that the ability to set frequency accurately is of prime importance in the selection of a frequency standard.

b. Types of Receivers

The best and most expensive Loran-C timing receiver is built by Collins Radio Company to meet IRIG Specification 107-62. This unit is essentially one channel of semiautomatic Loran-C navigation receiver, using synchronous detection and phase tracking servos to provide automatic phase tracking of one Loran-C signal - even in poor signal-to-noise ratios. Even this receiver requires an auxiliary oscilloscope for signal acquisition and needs manual adjustment of pulse envelope synchronization. At medium and long ranges (800 miles or more) even an experienced operator might synchronize on skywave signals instead of groundwave - a situation that should become obvious at sunrise and sunset when the skywave delay changes by 20 microseconds or more.

Simpler receivers, such as one built by Aerospace Corporation, have poorer performance in noise as a result of using fullwave rectification of the pulse signals to avoid the need for decoding the 180-degree phase coding of the signals. While this method is satisfactory in areas of good signal-to-noise ratios (better than 1:1), it suffers signal suppression at poorer ratios.

Other still simpler receivers, such as the EECO Model 885 which depends upon oscilloscope matching of the Loran-C pulse, are merely fixed-tuned amplifiers requiring separate timing circuits. These are satisfactory when close to the transmitting stations or when used for the less-accurate skywave measurement.

c. Use of Navigation Receivers for Timing

In situations where a Loran-C navigation receiver is available, such as aboard a ship or aircraft using Loran-C for navigation, clock synchronization signals can be made available by means of simple modifications to the receiver. An essential part of the clock synchronization process is the calculation of the distance to the Loran-C station. This step is actually an integral element in the solution of the navigation problem, and any vehicle using a computer to determine position by Loran-C should have this data continuously available. For example, the computed distance to each transmitter is one of the outputs of the AN/ARN-85 Loran navigation equipment.

Most Loran-C navigation receivers, such as the AN/WPN-3 and AN/ARN-78, generate internal waveforms which bear a known time relationship to the received Loran-C signals. It then becomes a relatively simple matter to extract a timing waveform related in a predictable manner to the Master (or Slave) Loran-C station. The absolute delay in the receiver system (unimportant to the navigation function, which is concerned only with time differences) becomes an item which must be measured and accounted for.

Overall accuracies of time synchronization will be somewhat poorer in a moving vehicle than at a fixed site because the averaging time will be shorter and errors in the range calculation will introduce timing errors. Overall clock-synchronization accuracies will be in the order of 0.5 microsecond over sea-water paths and probably 1.0 microsecond over long land paths.

3. Skywave Timing

a. General

At night, Loran-C skywaves have been received consistently out to ranges beyond 3500 nautical miles, thereby indicating that the use of skywave signals can greatly increase the useful coverage area of the system. (The daytime skywave range is generally limited to less than 2000 miles.) However, this nighttime increase in coverage is achieved only at the cost of decreased accuracy and availability. In moderate to high latitudes, nighttime conditions may be quite brief. For example, on 22 June 1958 signals from the east coast Loran-C chain were observed at Prestwick, Scotland for one-half hour at about 0230 GCT, the only period that the entire propagation path was in darkness. But even a half an hour per day can be used to provide clock synchronization - to an accuracy which depends on the nature of the skywave propagation path.

The relative amplitude of the various propagation modes is shown in figure 29 as a function of distance from the transmitter. As can be seen, at night the one-hop mode is dominant from about 400 to 1500 miles, the two-hop mode from 1500 to 2400 miles and the three-hop mode from 2400 to beyond 3500 miles.

Obviously, several modes are present simultaneously - particularly at the longer ranges. This condition can make identification of the modes difficult at certain ranges. In addition, the skywave amplitude may vary from the predicted value by 10 db or more depending upon seasonal and solar effects.

b. Error Budget

The error budget for skywave synchronization has the same elements as that for groundwave, except that the propagation errors become the dominant factor by an order of magnitude. The skywave propagation errors will now be discussed in detail.

(1) Propagation Errors. The accuracy of propagation of skywaves depends upon the identification of the particular skywave mode in use and the accuracy achieved in calculating the length of its propagation path. Assuming the mode to be known, the propagation time can be calculated in a straightforward manner. The groundwave propagation time must first be calculated, including the secondary phase correction. The one-hop skywave delay relative to the groundwave is readily determined from the curves of figure 30. To obtain n-hop propagation delay the one-hop curves are used, the range is divided by n, the corresponding delay is read, multiplied by n. The delays of figure 30 assume an effective ionosphere height of 90 km at night. Actually, delays corresponding to effective heights from 80 km to over 100 km at night have been measured on Loran-C signals. Deviations in the effective height cause corresponding deviations in delay that are approximately equal to

$$\Delta\ t\ (\mu\,\text{sec}) = N\Delta\ n\ (\text{KM})$$

at ranges where the n^{th} order mode is dominant.

In addition to the uncertainty of propagation time, there is the problem of proper separation of the various skywave modes, and the concomitant problem of cycle selection on the pulse representing that mode. Measurements on skywaves from the Loran-C East Coast Chain in New York and Boulder Colorado, and from the Hawaiian Chain on Wake Island indicate that a probable error of 1 cycle (10 microseconds) can be expected in nighttime skywave measurements of the first hop. Similar measurements on multiple-hop pulses can be expected to have a similar error.

Assuming a probable error of 5 km in ionosphere height and a 1-cycle envelope match error, the probable error of any measurement of skywave propagation time is

$$\varepsilon = (10 + 5\ n)\ \text{microseconds}$$

where n is the number of hops.

This error can obviously be reduced by averaging a number of measurements, provided the variables of ionosphere height and mode interference are random variables with mean values equal to the predicted values. This condition may be valid only over periods of weeks or months. However, since Loran-C is in constant use for navigation and the stations can monitor skywaves, measurement of ionospheric height can be made independently. This leaves cycle selection as the principal error source - an error which is, in many cases, impossible to resolve.

(2) Clock Error. Again, assuming a local frequency standard that can be set to 1 part in 10^{10} and which has an aging rate of 1×10^{-10} per day, the clock error in one day will be (from figures 17 and 18) 8.5 ±4.4, or 12.9 microseconds maximum. This is the same order of magnitude as the propagation error, indicating that with an ordinary good crystal standard synchronization once per day will provide as satisfactory an accuracy as can be expected.

TABLE 12. LORAN-C ERROR ANALYSIS SUMMARY FOR GROUNDWAVE AUTOMATIC TRACKING RECEIVER

Source of Error		Amount of Error (μsec)
Transmitting System		0.1
Survey		0.1
Receiving System		0.22
Clock		0.1
Propagation - Seawater		0.1
	RSS:	0.30 μsec
Propagation - Land		0.5 μsec
	RSS:	0.57 μsec

TABLE 13. LORAN-C ERROR ANALYSIS SUMMARY FOR GROUNDWAVE MANUAL RECEIVER

Source of Error		Amount of Error (μsec)
Transmitting System		0.10
Survey		0.10
Receiving System		0.22
Clock		0.36
Propagation - Seawater		0.10
	RSS:	0.46 μsec
Propagation Errors - Land		0.50 μsec
	RSS:	0.67 μsec

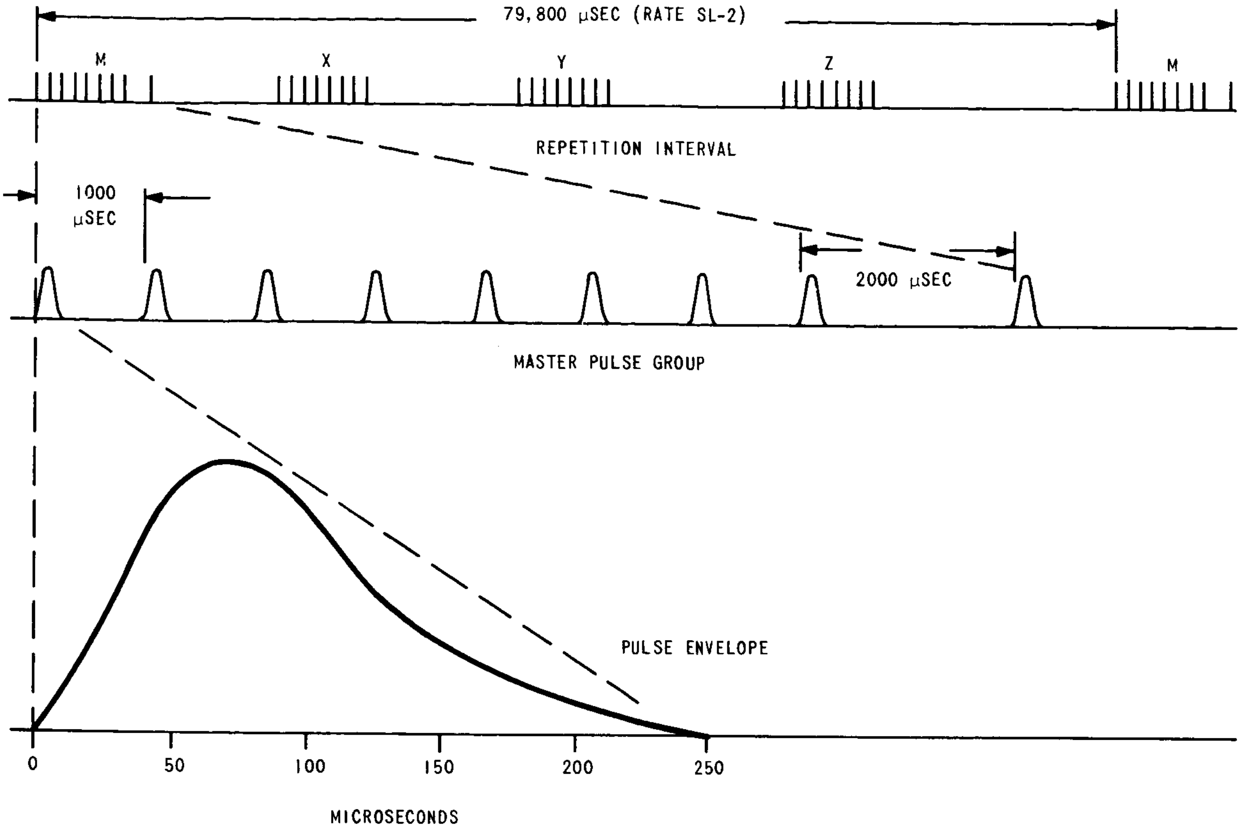
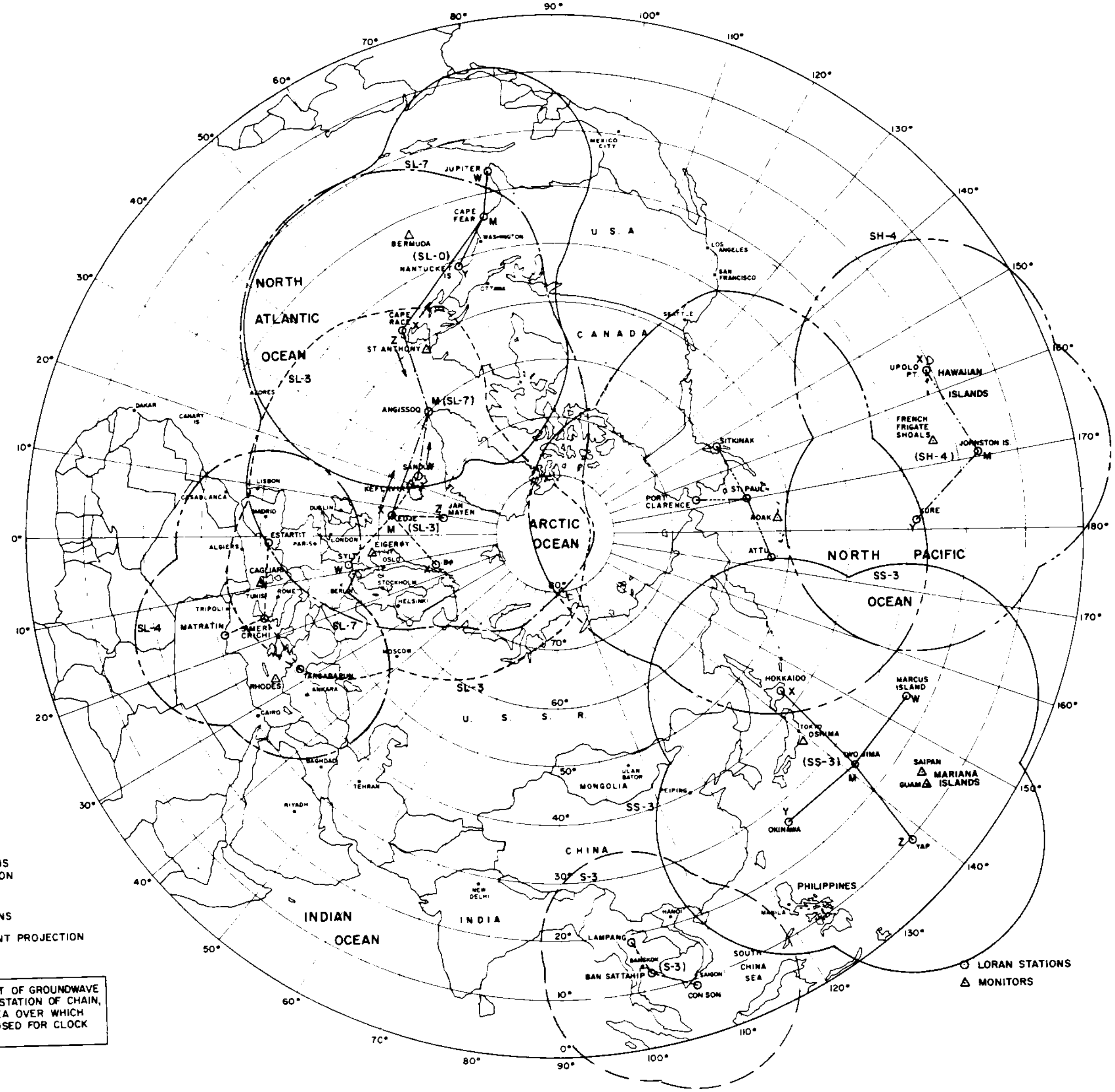


FIGURE 23. TYPICAL LORAN-C PULSES



LORAN-C
- OPERATING STATIONS
- UNDER CONSTRUCTION

STABILIZED VLF
- OPERATING STATIONS

AZIMUTHAL EQUIDISTANT PROJECTION
1 INCH = 0.632 MILE

CONTOURS SHOW LIMIT OF GROUNDWAVE FROM AT LEAST ONE STATION OF CHAIN, THUS ENCLOSING AREA OVER WHICH EACH CHAIN CAN BE USED FOR CLOCK SYNCHRONIZATION

FIGURE 24. TIME SYNCHRONIZATION CONTOURS OF 1966 LORAN-C CHAINS FOR NORTHERN HEMISPHERE

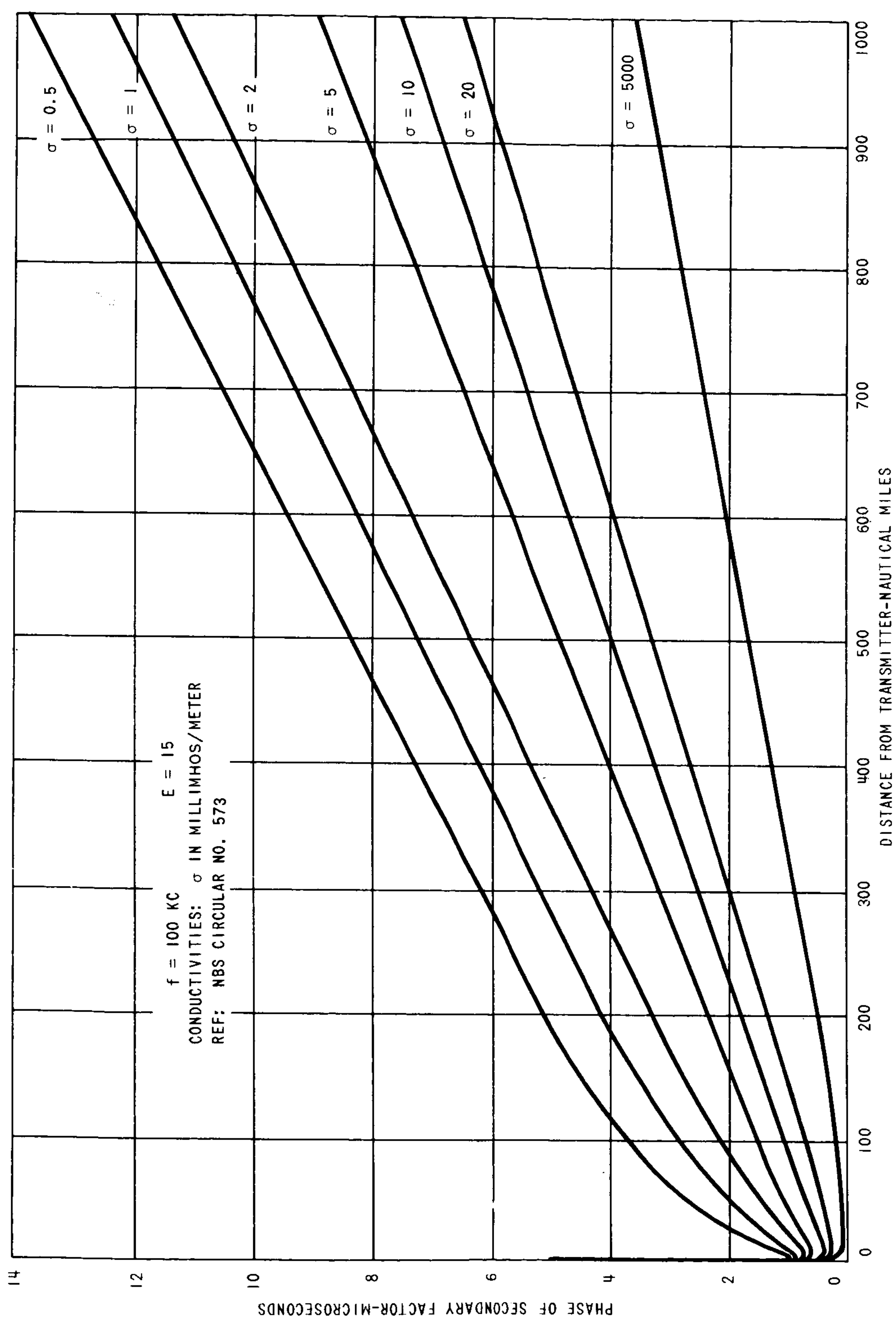


FIGURE 25. VARIATION OF SECONDARY FACTOR VS RANGE FOR DIFFERENT GROUND CONDUCTIVITIES

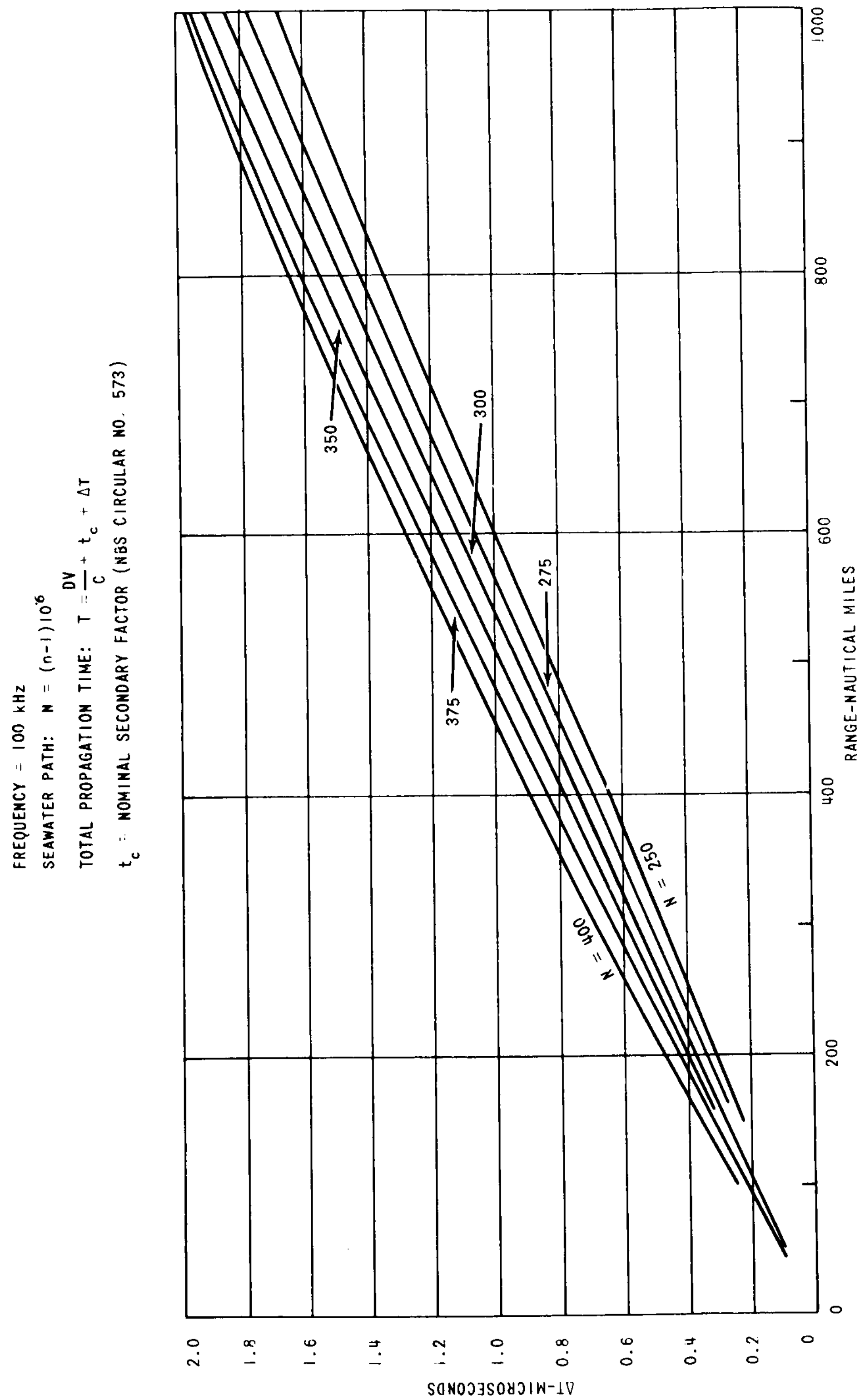


FIGURE 26. ADDITIONAL PROPAGATION DELAY CAUSED BY INDEX OF REFRACTION (INCLUDING LAPSE-RATE CHANGE) VS RANGE

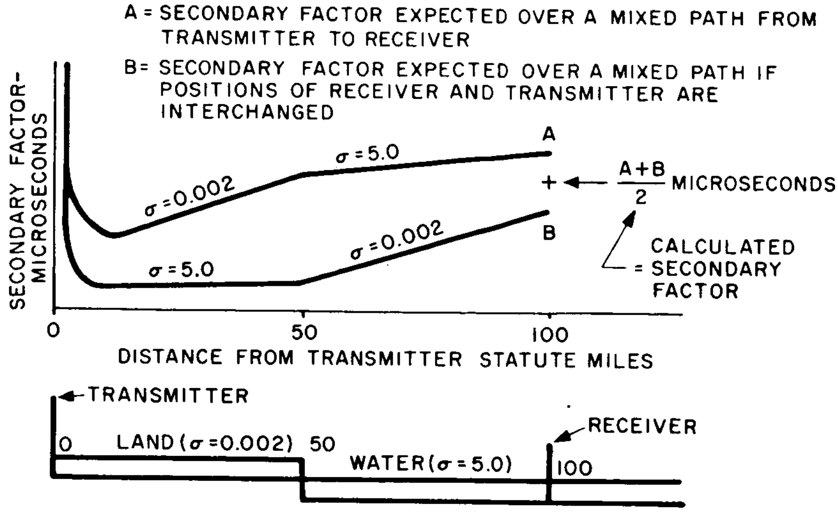


FIGURE 27. GRAPHICAL SOLUTION OF SECONDARY FACTOR OVER MIXED PATH

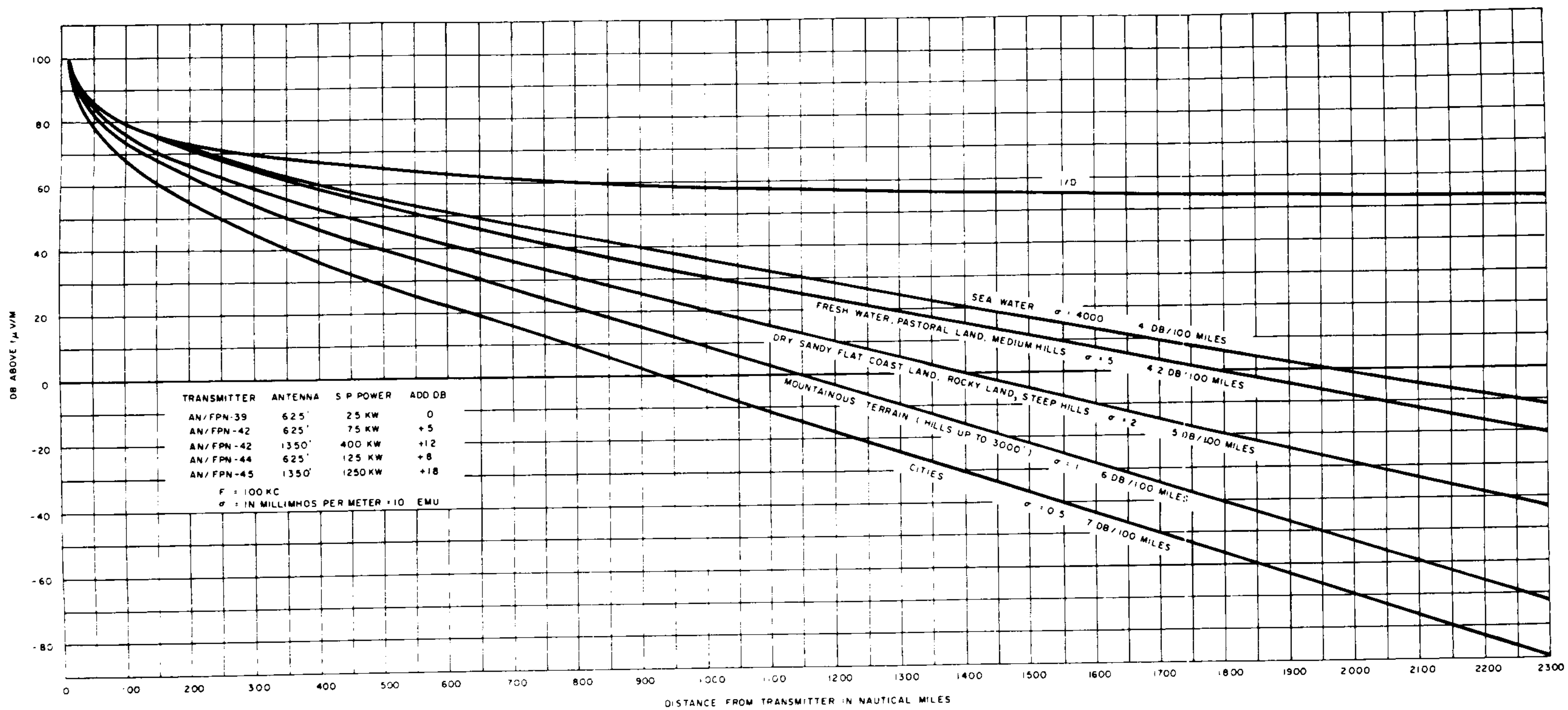


FIGURE 28. LORAN-C FIELD INTENSITY VS RANGE AND EARTH CONDUCTIVITY

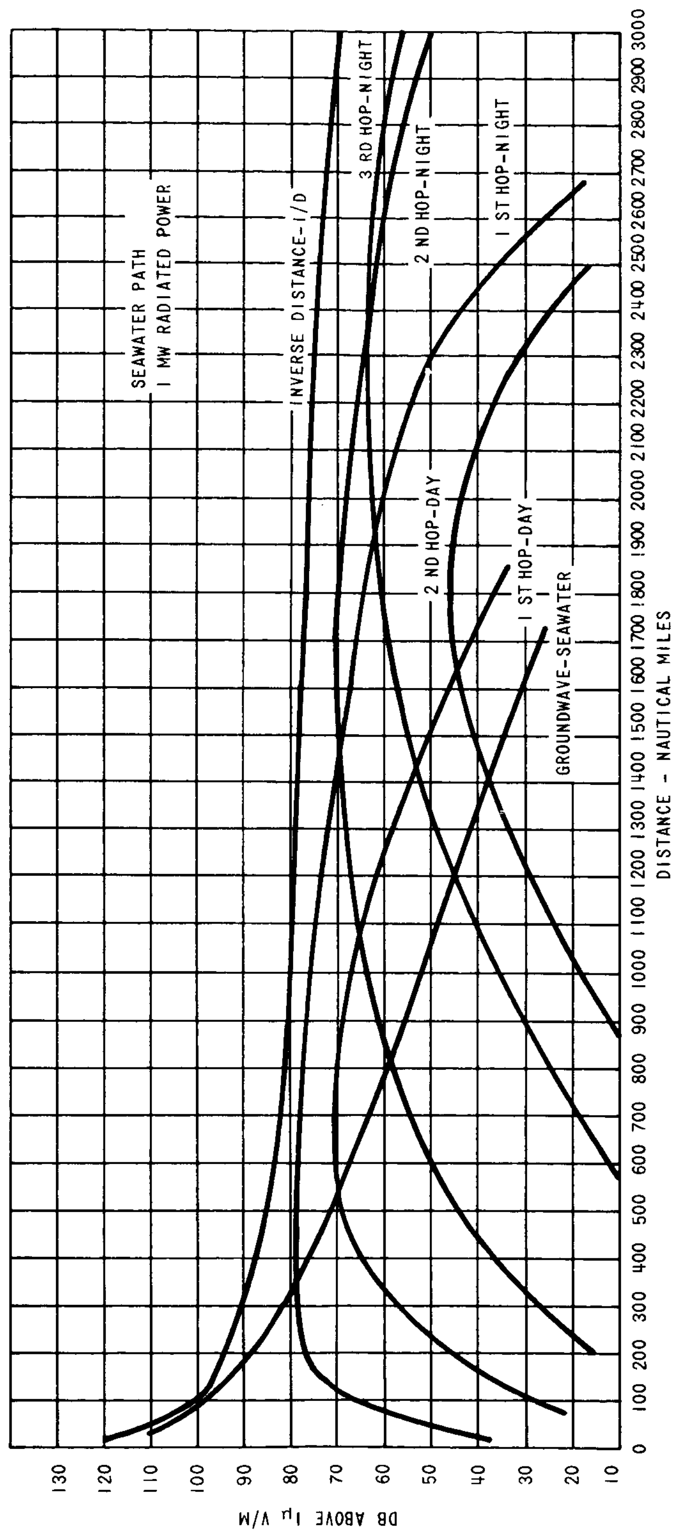


FIGURE 29 SKYWAVE FIELD INTENSITY VS RANGE AT 100 KHz

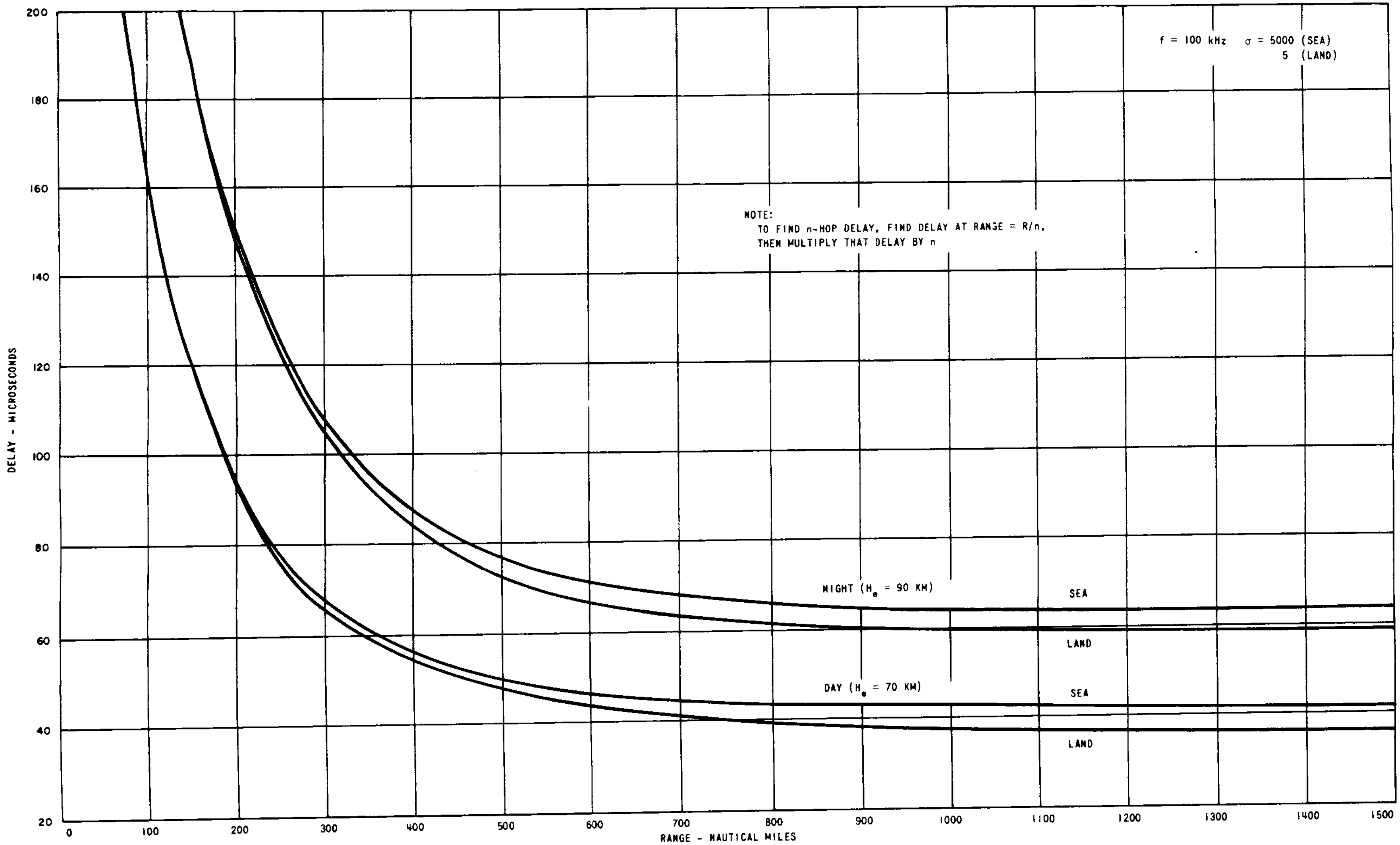


FIGURE 30. ONE-HOP SKYWAVE DELAY VS RANGE

SECTION VII

MEDIUM FREQUENCIES

A. INTRODUCTION

Medium frequencies, operating with medium bandwidth modulation, are useful at medium ranges. The use of these frequencies for clock synchronization is limited by this fact - particularly in day time when skywave absorption is high.

Coarse time signals, which are probably accurate to approximately 0.5 second, are obtainable from standard broadcast stations. Relative synchronization between stations 100 miles apart has been accomplished by E.A. Lewis of AFCRL by recording the modulation of a broadcast station at both sites, along with the desired data. Subsequent correlation of the modulation patterns provided relative time synchronization of the data - to the accuracy of the recording. This technique can be used to provide synchronization within a few milliseconds, if desired, but not on a real-time basis.

The Loran-A system, presently installed in many areas around the world, can provide microsecond relative timing over moderate size areas. This system will now be described.

B. LORAN-A

1. Functional Description

Loran-A can be used to synchronize clocks to one another - within certain areas less than 1000 miles in radius - to an accuracy of about 2 microseconds. At night, skywaves can be used over areas of approximately 2000 miles' radius to obtain synchronization to about 5 microseconds. Almost all Loran-A pairs operate at repetition rates not related to the second, and none is coordinated with Universal Time.

The Loran-A system operates in the frequency band from 1750 to 1950 kHz. At present three frequency channels are in use: channel 1 - 1950 kHz; channel 2 - 1850 kHz; and channel 3 - 1900 kHz. Each station transmits one pulse per Loran sequence and each pair of stations is assigned a specific pulse repetition rate.

Specific pulse repetition rates (PRR) are derived from the three basic repetition rates of 20, 25, and 33-1/3 pulses per second (designated (S), (L), and (H), respectively). Specific repetition periods for specific PRR's, zero through 7, are derived by subtracting multiples of 100 microseconds from the basic repetition periods.

Loran-A pairs are designated by their basic characteristics in the following order: frequency channel, basic repetition rate, and specific repetition period. For example, 1L3 denotes a Loran-A pair having a frequency of 1950 kHz, a basic repetition rate of 25 Hz, and a specific repetition period of 39,700 microseconds.

The Loran-A pulse shape is a cosine-squared pulse whose rise-time is measured from the 10- to 90-percent amplitude points of the leading edge of 20 microseconds and whose pulsewidth measured at the 50-percent amplitude level is 40 microseconds.

Loran-A receivers use a two-trace oscilloscope presentation. To accommodate the station transmissions to this presentation, it is necessary to delay the Slave transmission by one-half the pulse repetition period after receipt of the Master signal. This delay period is referred to as the reference delay. The coding delay for Loran-A consists of this reference delay plus a finite delay of 1000 or 500 microseconds.

Loran-A stations are arranged in pairs having baselines from 200 to 700 miles in length. Specific rates are selected to provide freedom from interference from other pairs. Since fix coverage is normally required, a third station is provided to form a second pair, resulting in a Loran triad. The common station operates on both specific repetition rates, performing either double or mixed functions.

2. Utilization of Loran-A for Clock Synchronization

a. Usable Synchronization Ranges. Limited clock synchronization using Loran-A stations is feasible, but the system is not generally so used. Although approximately 60 pairs of Loran-A stations border the Atlantic and Pacific oceans (see figure 31), coverage for synchronization is limited to the area covered by any one pair because each chain operates independently. The stations are not tied to world time, and thus represent 60 independent systems.

The area over which clocks can be synchronized using Loran-A is limited to the area in which signals from either of a pair of Loran-A transmitters can be received. The field strengths expected from a 100-kw transmitter at 2 MHz (ref. 102) are shown in figure 32, in which two features should be specially noted: The signal strength at 700 miles over seawater is about equal to the signal strength at 120 miles over land, which means that overland coverage of the groundwave is extremely limited; the one-hop, E-night skywave is strong out to 1500 miles, providing greater range but only with lower accuracy. The skywave signals propagate over land nearly as well as over seawater, thus making skywave coverage considerably greater than that of groundwave signals.

The range of transmission is dependent upon the ambient noise level. At 2 MHz the signal required for satisfactory Loran-A operation is about 5 microvolts/meter in the middle latitudes in daytime, which corresponds to a maximum range of about 700 nautical miles - the nominal radius of the Loran service area.

The magnitudes of the required signals and the usable ranges for standard Loran groundwaves over seawater are given in table 14.

TABLE 14. REQUIRED SIGNALS AND USABLE GROUNDWAVE RANGES FOR STANDARD LORAN OVER SEAWATER

Latitude	Season	Day		Night	
		Required Signal (Uv/Meter)	Range, (Nm)	Required Signal (Uv/Meter)	Range, (Nm)
Equatorial		25	550	250	400
Middle	Summer	5	700	50	500
	Winter	1	850	10	650
Arctic	Summer	1	850	10	650
	Winter*	1	850	1	850

*The range in winter in quiet regions is limited by the finite sensitivity of the Loran receiver.

The ranges listed in the table are approximate, and day-to-day variations of considerable magnitude do occur. A thunderstorm, for instance, if close to the receiver, will produce an effect very similar to that of tropical night conditions.

b. Clock Synchronization Error Budget. The over-all error of clock synchronization is a function of the following parameters:

- Transmitting system errors
- Survey errors
- Propagation errors
- Receiving system errors
- Clock errors.

These will now be discussed and evaluated in turn.

(1) Transmitting System Errors. These errors result from instabilities in the Master station and variations in the coding delay of the Slave station relative to the Master. These variations are generally held to less than 0.5 microsecond.

(2) Survey Errors. All the Loran stations have been surveyed quite accurately. The position information is available from the U.S. Coast Guard to an accuracy in the order of 100 ft - which does not contribute to the errors of this synchronization system.

(3) Propagation Errors. The predictability of groundwave propagation of the Loran-A pulses can be inferred from the fact that the U.S. Navy Oceanographic Office in preparing Loran-A charts uses the following values of velocity-of-propagation:

- 299.708 meters/microsecond for new stations not at high latitudes, and
- 299.692 meters/microsecond for old stations and new stations at high latitudes.

The difference between these two velocities produces a difference of 0.2 microsecond over a 1000-km (540-nm) path; i.e., close to the maximum groundwave range for Loran-A.

Skywave signals reflected from the E- and F-layers can be received only at night. This mechanism is illustrated in figure 12 which shows the relative amplitude and time-of-arrival of the various modes. The one-hop, E-layer reflection is the most reliable - out to about 1500 nautical miles.

For skywave propagation, Pierce (ref. 102) collected data (figure 33) taken in the 1940's on the probable error of skywave delay measurements. The data given in this illustration represents the probable error of a single transmission time, not of a Loran reading. The transmission time of 6000 microseconds corresponds to a 970-nautical-mile range. This range indicates that the probable timing error, using the 1-hop E, will be in the order of 5 microseconds.

F-layer propagation is considerably less predictable. As seen in figure 33, the F-layer reflections are unsuitable for use in precise timing since they undergo considerable distortion in the process of propagation because of the generation of multiple paths. In addition, the effective layer height varies to such an extent that the path length is not readily predictable to better than ±50 microseconds.

(4) Receiving System Errors. In using Loran-A for clock synchronization, it will be necessary to use an oscilloscope and visually align a local reference marker with the received Loran-A pulse. The most accurate method would

be to generate within the oscilloscope an internal pulse identical in shape to the Loran-A pulse and then align the leading edges of the two pulses visually in the same manner as the normal operation of a Loran-A receiver. The probable error of such an operation is approximately 1 microsecond.

Calibration of the internal delay of the receiver could be accomplished by making the reference pulse an rf signal and feeding it into the input of a Loran-A receiver.

(5) Clock Errors. Since Loran-A is a manually operated system, the local clock can drift between settings. Reference to figures 17 and 18 provides basic information on the effects of frequency offset and aging rate. Assuming a high quality, crystal-controlled frequency standard with an aging rate of 1×10^{-11} per day, an error of 0.43 microsecond will result in one day from aging. If the frequency is set (or calibrated) to 1×10^{-11}, an error of 0.86 microsecond will accumulate in one day.

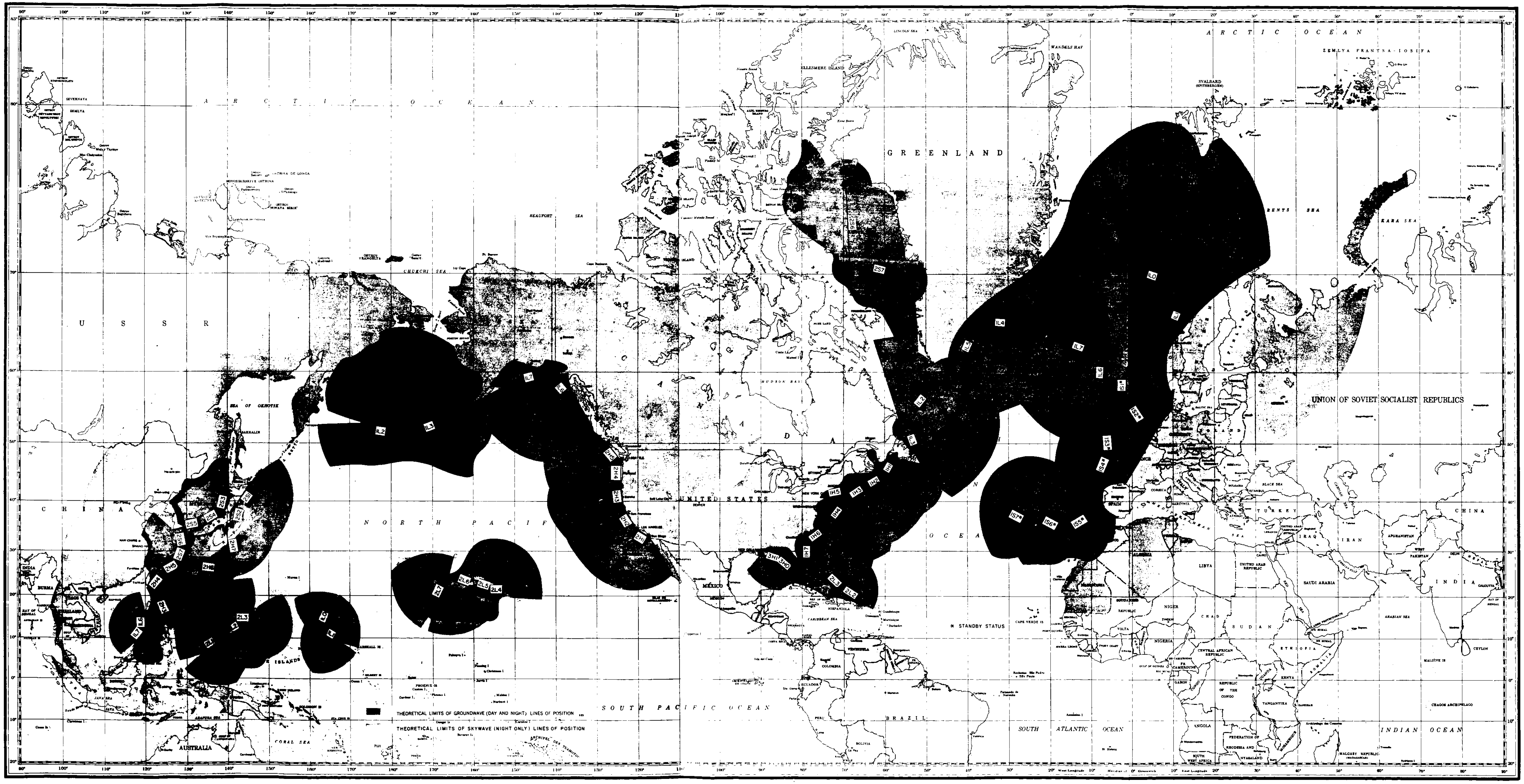


FIGURE 31. LORAN-A WORLD COVERAGE MAP

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FIG. 31	CONTRACT NO. NAS 5-9905 (SPERRY REPORT NO. HB-9224-0234)

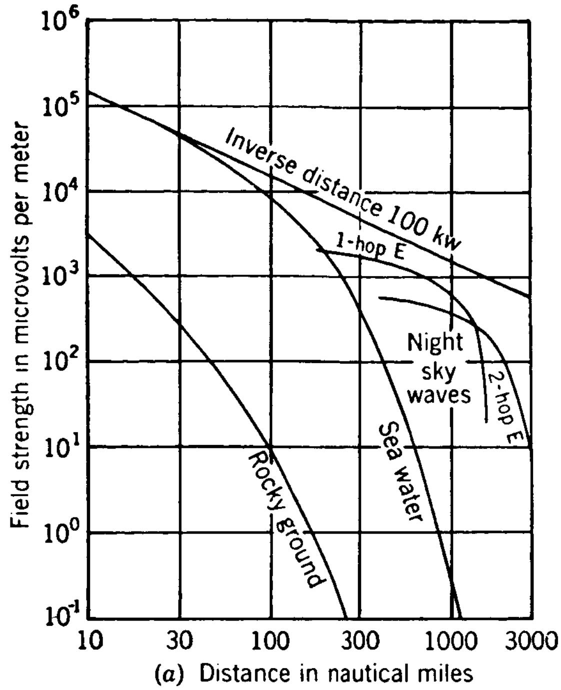

FIGURE 32. LORAN-A FIELD STRENGTH VS RANGE FOR 100-Kw OUTPUT AT 2MHz

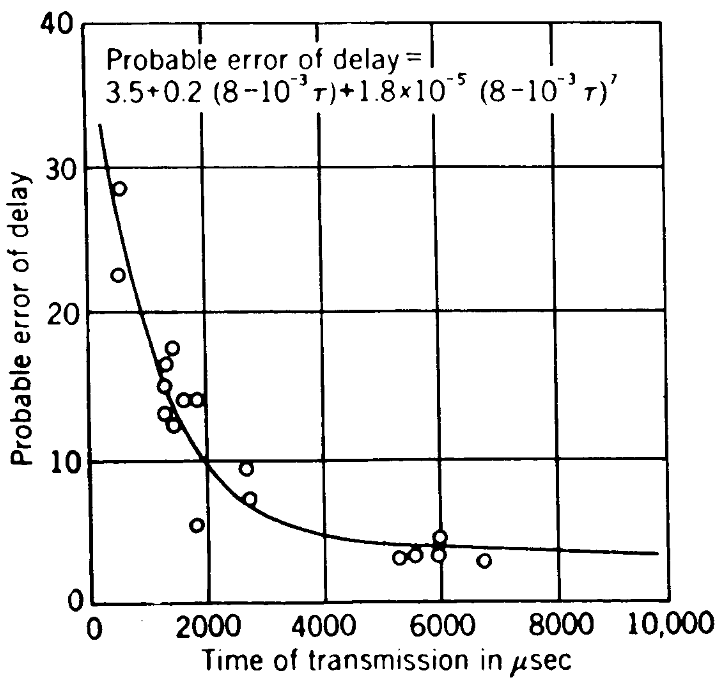

FIGURE 33. OBSERVATION OF SKYWAVE DELAY AT 2MHz

SECTION VIII

HIGH FREQUENCY RADIO AND LINE-OF-SIGHT SYSTEMS

A. INTRODUCTION

High frequency radio may be employed in a number of ways for clock synchronization. This section discusses the most widely used method: standard time-signal transmission broadcast from a number of stations around the world.

Standard time signals, held in synchronism with coordinated UT2 time (designated UTC), are broadcast by stations in Europe, North and South America, and Asia on frequencies from 2. 5 to 25 MHz. The variety of sources and frequencies utilized makes it possible to receive time signals most of the time at any point on earth. The accuracy to which time can be determined from these signals is limited principally by the variations in propagation time of the signals. These propagation errors also cause an error in synchronization between the transmitting stations and UTC.

Clock synchronization accuracies of better than 1 millisecond can be achieved with minimum cost by using a moderately good clock and relatively simple receiving equipment.

B. SYSTEM DESCRIPTION

Certain radio stations in various parts of the world broadcast time signals on standard frequencies which they attempt to control to an accuracy of 1 millisecond of coordinated UT2 time (UTC). These stations, listed in table 15, include WWV and WWVH[4] which are maintained by NBS to within 25 microseconds of each other. The daily emission schedules and hourly modulation schedules for these standard time stations are given in figures 34 and 35, respectively. The reference for UTC is the Bureau International de l'Heure (BIH) in Paris, France, which monitors the time signals broadcast by the cooperating stations. BIH issues a publication, "Bulletin Horaire," listing the observed time errors of each to the nearest 0. 1 millisecond, as illustrated by table 16, which lists typical calibration data as reported for the months of January and Febrary 1965, and for May and June 1965.

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[4] Located in Beltsville, Md., and Kihei, U. S. A., respectively.

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS

Characteristics of Hourly Signal Emissions (February 1966)[1]

a - Signal Coordinates (Shifting Frequencies of $-300 \; 10^{-10}$ from 1 January 1966 at 0 Hour UT)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
CHU	Ottawa, Canada	$+45^{\circ} 18'$ $+75^{\circ} 45'$	3330; 7335; 14670	Continuous	Impulses of 200 cycles of modulation at 1000 Hz. Certain impulses are omitted.	50
DAM	Elmshorn, F. R. of Germany	$+53^{\circ} 46'$ $-9^{\circ} 40'$	8638.5; 16980 4265; 8638.5	11 hours 55 minutes to 12 hours 6 minutes, UT 23 hours 55 minutes to 24 hours 6 minutes, UT from 21 September to 20 March	ONOGO, in English, type A1[2]	
			6475.5; 12763.5	23 hours 55 minutes to 24 hours 6 minutes, UT from 21 March to 20 September		
DAN	Norddeich, F. R. of Germany	$+53^{\circ} 36'$ $-7^{\circ} 8'$	2614	11 hours 55 minutes to 12 hours 6 minutes 23 hours 55 minutes to 0 hours 6 minutes, UT	ONOGO, in English, type A1	

Notes: [1]From "Bulletin Horaire," Serie J, No. 7, January-February 1965, published by the Bureau Internationale de l'Heure, Paris, France

[2]The signals of the English type include the impulses at 1 Hz during the 5 minutes which precede the hours indicated.
The impulses of the "even" minutes are lengthened.
The telegraphic signals of type A1 are produced through emission of the carrier.
The rhythm signals include 61 impulses equidistant by 60 seconds.
The signals of the ONOGO type are those of the international system.

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
DCF77	Mainflingen, F.R. of Germany	$+50^{\circ}$ 1' -9° 0'	77.5	7 hours; 10 hours; 19 hours; 19 hours, 30 minutes; 20 hours; 21 hours; 22 hours; 23 hours; 0 hour; 1 hour; 2 hours; UT No emission from the 19th hour on Saturday to the 10th hour on Sunday. The emissions of the first hour and 2nd hour are broadcast from 1 March to 31 October only.	Type A1 of the German Hydrographic Institute between the first and tenth minutes of every other hour	
DIZ	Nauen, D.R. of Germany	$+52^{\circ}$ 39' -12° 55'	4525	Continuous		
FFH	Chevannes, France	$+48^{\circ}$ 32' -2° 27'	2500	Between 9 minutes 45 seconds and 20 minutes, 30 minutes and 40 minutes, 49 minutes 45 seconds and 60 minutes; from 8 hours to 16 hours 25 minutes, except on Saturday and Sunday.	Impulses of 5 cycles of modulation at 1 kHz. The minute signal is lengthened by a modulation at 500 Hz.	2
FTA91	St. Andre' de Corcy, France	$+45^{\circ}$ 55' -4° 55'	91.15	At 8 hours; 9 hours; 9 hours 30 minutes; 13 hours; 20 hours; 21 hours; 22 hours 30 minutes, UT	English, type A1	

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
FTH42 FTK77 FTN87	Pontoise, France	$+49^{\circ}\ 4'$ $-2^{\circ}\ 7'$	7428 10775 13873	At 9 hours and 21 hours, UT; at 8 hours and 20 hours, UT; at 9 hours 30 minutes; 13 hours; 22 hours 30 minutes, UT	English, type A1	
GBR[3]	Rugby, United Kingdom	$+52^{\circ}\ 22'$ $+1^{\circ}\ 11'$	16	At 3 hours; 9 hours; 15 hours; 21 hours, UT[1]	English, type A1	1
GIC27 GIC33 GIC37 GPB30B	Rugby, United Kingdom	$+52^{\circ}\ 22'$ $+1^{\circ}\ 11'$	7397.5 13555 17685 10331.5	At 9 hours and 21 hours, UT[3]	Depending upon the season, one or more emissions at 9 hours and 21 hours, UT. English, type A1 (emitted simultaneously with MSF and GBR).	
HBG	Prangins, Switzerland	$+46^{\circ}\ 24'$ $-6^{\circ}\ 15'$	75	Continuous	Suppression of the carrier at the beginning of each second and during 0.1 second. A second suppression follows the signal of the "even" minute.	Frequency carrier (non-shifting)

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[3]During the first six months of 1966, the emission of GBR was suspended and replaced by GBZ (19.6 kHz), location CRIGGION (latitude: $+52^{\circ}43'$, longitude $+3^{\circ}4'$). Same service as GBR.

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
HBN	Neuchâtel, Switzerland	$+46^{\circ}$ 58' -6° 57'	5000	Between minutes 5 and 10, 15 and 20, 25 and 30, and 35 and 40 of each hour.	Interruption of the 1-ms carrier is repeated 5 times per second and 250 times at the beginning of a minute. The correct hour corresponds to the beginning of the first interruption.	1
IAM	Rome, Italy	$+41^{\circ}$ 52' -12° 27'	5000	From 7 hours 30 minutes to 8 hours 30 minutes, UT; 10 minutes every 15 minutes except Sunday.	Impulses of 5 cycles of modulation at 1 kHz. The first impulse of each minute is repeated 4 times.	5
IBF	Turin, Italy	$+45^{\circ}$ 3' -7° 40'	5000	From 6 hours 50 minutes to 7 hours 30 minutes and 10 hours 50 minutes to 11 hours 30 minutes, UT, except Sunday	Impulses of 5 cycles of modulation at 1 kHz. The impulse of the "even" minute is repeated 7 times.	50
JAS22	Oyama, Japan	$+36^{\circ}$16' -139° 48'	16170	From 12 hours 25 minutes to 12 hours 30 minutes, UT.	English, type A1 (emitted simultaneously with JJY).	
JJY	Koganei, Japan	$+35^{\circ}$ 42' -139° 31'	2500; 5000 10000; 15000	Continuous interruptions between minutes 25 and 34.	Impulses of 8 cycles of modulation at 1600 Hz. The impulse of the "even" minute is preceded by a modulation of 600 Hz.	5

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
LOL1	Buenos Aires, Argentina	-34° 27' $+58^{\circ}$ 21'	5000; 10000 15000	0 hour to 1 hour; 12 hours to 13 hours; 15 hours to 16 hours; 18 hours to 19 hours; 21 hours to 22 hours, UT; suspended for one hour between 1 October and February 28 or 29.	Impulses of 5 cycles of 1000 Hz. The 59th second is omitted. Announces the hours and minutes every 5 minutes, depending upon 3 minutes of modulation at 1000 and 440 Hz in alternation.	10
LOL2 LOL3	Buenos Aires, Argentina	-34° 37' $+58^{\circ}$ 21'	8030, 17180	1 hour; 13 hours; 21 hours, UT	English, type A1.	
MSF	Rugby, United Kingdom	$+52^{\circ}$ 22' $+1^{\circ}$ 11'	60 2500; 5000 10000	From 14 hours 30 minutes, to 15 hours 30 minutes, UT; 5 minutes every 10 minutes (Alternates with HBN)	Impulses of 5 cycles of modulation at 1 kHz. The impulse of the "even" minute is lengthened.	1
NBA	Balboa, Panama Canal Zone, U.S.A.	$+9^{\circ}$ 4' $+79^{\circ}$ 39'	147.85; 5448.5 11080; 17697.5	5 hours; 10 hours; 17 hours; 23 hours, UT	English, type A1. Certain impulses are omitted.	
NPG	Mare Island, U.S.A.	$+38^{\circ}$ 6' $+122^{\circ}$ 16'	114.95; 4010; 6428.5; 9277.5 12966; 17055.2 22635	6 hours; 12 hours; 18 hours; 24 hours, UT	English, type A1. Certain impulses are omitted.	

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
NPM	Lualualei, U.S.A.	$+21^{\circ}$ 25' $+158^{\circ}$ 9'	131.05; 4525 9050; 13655 17122.4; 22593	6 hours; 12 hours; 18 hours; 24 hours, UT	English, type A1. Certain impulses are omitted.	
NPN	Guam, U.S.A.	$+13^{\circ}$ 27' -144° 43'	484; 4955 8150; 13530 17530; 21760	6 hours; 12 hours; 18 hours; 24 hours, UT	English, type A1. Certain impulses are omitted.	
NSS	Annapolis, U.S.A.	$+38^{\circ}$ 59' $+76^{\circ}$ 27'	162; 5870 9425; 13575 17050.4; 23650	2 hours; 6 hours; 8 hours; 12 hours; 14 hours; 18 hours; 24 hours, UT	English, type A1. Certain impulses are omitted.	
OLB5 OLD2	Satalice, Czechoslovakia	$+50^{\circ}$ 7' -14° 35'	3170 18985	Continuous, except from 10 hours to 11 hours, UT; 12 hours 30 minutes to 13 hours, UT; Wednesdays and Fridays	Type A1, impulses to the second. Type A1, impulses to the second.	
OMA	Podebrady, Czechoslovakia	$+50^{\circ}$ 8' -15° 8'	50	Continuous, except from 10 hours to 11 hours, UT	Type A1, impulses to the second.	10
OMA	Satalice, Czechoslovakia	$+50^{\circ}$ 7' -14° 35'	2500	Between minutes 5 and 15, 25 and 30, 35 and 40, 50 and 60 of each hour.	Impulses of 5 cycles at 1000 Hz. Certain impulses are lengthened (these are given in "even" minutes).	10

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
PPE	Rio de Janeiro, Brazil	-22° 54'	8720	0 hour 30 minutes; 13 hours 30 minutes; 2 hours 30 minutes, UT		
PPR		$+43^{\circ}$ 11'	1305; 4244; 6421; 8634; 17194	1 hour 30 minutes; 14 hours 30 minutes; 21 hours 30 minutes, UT	English, depending upon rhythm[3]	
VHP	Belconnen, Australia	-35° 15'	44	3 hours, except for Tuesday and Wednesday, and 8 hours, UT		
		-149° 8'	4286; 6428.5; 8478; 12907.5 17256.8	3 hours; 8 hours; 14 hours; 20 hours, UT	English, certain impulses are omitted.	
			22485	3 hours; 8 hours, UT		
VNG	Lyndhurst, Australia	-38° 0' -145° 2'	5425	12 hours 15 minutes at 22 hours, UT	Impulses of 100 cycles of modulation at 1 kHz. The 59th second is omitted.	10
			7515	Continuous		
			12005	22 hours 15 minutes at 12 hours, UT		
WWV	Beltsville, U.S.A.	$+39^{\circ}$ 0' $+76^{\circ}$ 51'	2500; 5000; 10000; 15000; 20000; 25000	Continuous, except for the 45th minute to the 48th minute	Impulses of 5 cycles of modulation at 1 kHz. The 59th second is omitted and the 0 second is repeated. Code is announced in days, hours and minutes.	1

TABLE 15. WORLD SOURCES OF UTC TIME BROADCASTS (Cont.)

Call Sign	Place	Latitude Longitude	Frequencies in kHz	Duration of Transmission of Hourly Signals	Signal Form	Frequency Accuracy in 10^{-10}
WWVH	Kihei, U.S.A.	$+20^{o}$ 46' $+156^{o}$ 28'	2500; 5000; 10000; 15000	Continuous, except between minutes 15 and 19.	Impulses of 6 cycles of modulation at 1200 Hz. The 59th second is omitted.	1
ZUO	Olifantsfontein, Rep. of South Africa	-25^{o} 58' -28^{o} 14'	5000	Continuous		
ZUO	Johannesbourg, Rep. of South Africa	-26^{o} 11' -28^{o} 4'	10000	Continuous		

TABLE 16. TYPICAL TABLES OF TIME ERRORS FOR UTC SOURCES AS REPORTED IN "BULLETIN HORAIRE"

Part A: Observed Data for January and February 1965†

Heure définitive de l'émission des signaux horaires coordonnés.

1°) Temps coordonné.

Date	J.J. 2438	TU2 déf - TUC à 0h TU (en $0^s_,0001$)	A3 - TUC à 0h TU	Notes
1965 jan. 4	764,5	9799	$3^s_,5435$	(1) TUC a été
9	769,5	9770	5499	retardé de
14	774,5	9738	5563	100 ms, le
19	779,5	9702	5628	1er mars
24	784,5	9663	5693	1965 à 0hTU
29	789,5	9624	5758	
fév. 3	794,5	9585	5823	
8	799,5	9548	5888	
13	804,5	9508	5953	
18	809,5	9470	6018	
23	814,5	9434	6083	
28	819,5	9394 (1)	6148 (1)	
mars 5	824,5	0354	7212	

2°) Ecarts individuels E : E = (TUC - Signal) émis.

Signal	fréquence en kHz	E en $0^s_,0001$ jan.	fév.
CHU*(1)	toutes fr.	+ 14	+ 17
DAM*	toutes fr.	- 1	0(2)
DAN	2614	+170(3)	+164
DCF77(4)	77,5	- 10	0
DGI*	186	-194	-196
DIZ*	4525	- 86	- 87
FFH	2500	- 1	- 7(5)
FTA91*	91,15	+ 51	+ 58
FTH42*(6)	7428	+ 2	+ 8
HBB*	96,05	0	0
HBN	5000	- 9	- 11
IAM	5000	+ 37	+ 40(5)
IBF	5000	+ 20	+ 5
JAS22	16170	- 16	- 23
JJY	toutes fr.	- 1	- 2
LOL*	toutes fr.	- 4	- 3
MSF*(7)	toutes fr.	0	- 1
NBA	toutes fr.(8)	+29	+46(5)
NPG	toutes fr.	-64	-39(5)
NPM	toutes fr.	- 1	-30(5)
NSS	toutes fr.	+ 4	+ 1
OLB5(9)	3170	+15	+19
OMA*	50	+ 4	+ 9
OMA*	2500	- 5	- 1
WWV*	toutes fr.	+ 1	+ 2
WWVH*	toutes fr.	- 1	+ 1
ZUO	toutes fr.	- 2	+ 2

Notes : (1)* indique que le calcul de (TU2 déf - Signal) émis, à une date quelconque par l'interpolation du tableau 7 n'introduit pas d'erreur supérieure à $0^s_,0003$. Pour les autres signaux, cette erreur est comprise entre $0^s_,0004$ et $0^s_,0010$, sauf mention contraire. (2) $+0^s_,0010$, du 14 au 18 février inclus. (3) $+0^s_,0191$ jusqu'au 6 janvier inclus. (4) signaux émis par le DHI. (5) irrégulier (± 2 ms). (6) et signaux FTK77, FTN87.
(7) et signaux associés : GBR, GPB30B, GIC27, GIC33, GIC37.
(8) sauf 24 kHz. (9) et OLD2 (18985 kHz).

†Reproduced from "Bulletin Horaire" of the Bureau International de l'Heure (BIH), Serie J, No. 7, Jan. - Fev. 1965, p. 21.

TABLE 16. TYPICAL TABLES OF TIME ERRORS FOR UTC SOURCES AS REPORTED IN "BULLETIN HORAIRE" (CONT)

Part B: Observed Data for May and June 1965†

Heure définitive de l'émission des signaux horaires coordonnés.

1°) Temps coordonné

Date	J.J. 2438	TU2déf - TUC à 0h TU (en $0^s.0001$)	A3 - TUC	Notes
1965 mai 4	884,5	9843	$+3^s.7993$	(1) TUC a été retardé de 100ms le 1er juillet 1965 à 0h TU.
9	889,5	9802	8058	
14	894,5	9759	8123	
19	899,5	9715	8188	
24	904,5	9664	8253	
29	909,5	9615	8318	
juin 3	914,5	9567	8383	
8	919,5	9522	8447	
13	924,5	9481	8512	
18	929,5	9437	8577	
23	934,5	9389	8642	
28	939,5	9342 (1)	8707 (1)	
juil.3	944,5	0297	9772	

2°) Ecarts individuels E : E = (TUC - Signal) émis.

Signal	fréquence en kHz	E en $0^s.0001$ mai	juin	Signal	fréquence en kHz	E en $0^s.0001$ mai	juin
CHU*(1)	toutes fr.	+ 18	+ 20	LOL	toutes fr.	- 1	- 6
DAM	toutes fr.	+ 5	+ 4	MSF*(6)	toutes fr.	0	- 3
DAN*	2614	+205	+ 28(2)	NBA	ondes courtes	+13	+ 14
DCF77(3)	77,5	- 6	- 7	NPG(7)	toutes fr.	-98	-116
DGI*	186	-174	-170	NPM	toutes fr.	+24	+ 36
DIZ*	4525	- 64	- 60	NSS*	21,4	-25	- 25
FFH(4)	2500	- 12	- 18	NSS	autres fr.	+ 5	+ 6
FTA91*	91,15	+ 47	+ 49	OLB5(8)	3170	+18	+ 9
FTH42* (5)	7428	- 5	- 3	OMA*	50	+ 9	+ 6
HBB*	96,05	- 1	- 3	OMA*	2500	- 2	- 4
HBN*	5000	- 14	- 16	WWV*	toutes fr.	0	0
IAM	5000	+ 70	+ 55	WWVH*	toutes fr.	- 6	- 7
IBF*	5000	+ 2	+ 3	ZUO*	toutes fr.	- 4	- 1
JAS22*	16170	- 23	- 20				
JJY	toutes fr.	- 4	- 6				

Notes. (1) * indique que le calcul de (TU2 déf - Signal) émis, à une date quelconque, par l'interpolation du tableau 7, n'introduit pas d'erreur supérieure à $0^s.0003$. Pour les autres signaux, cette erreur est comprise entre $0^s.0004$ et $0^s.0010$, sauf mention contraire.

(2) DAN a été avancé de 18 ms le 10 juin 1965.

(3) Signaux émis par le DHI.

(4) Irrégulier (± 2 ms).

(5) et FTK77, FTN87.

(6) et signaux associés : GBR, GPB30B, GIC27, GIC33, GIC37.

(7) Irrégulier (± 3 ms).

(8) et OLD2 (18985 kHz).

†Reproduced from "Bulletin Horaire" of the Bureau International de l'Heure (BIH), Serie J, No. 9, Mai - Juin 1965, p. 6.

Stations WWV and WWVH also broadcast the correction between the broadcast time and UT2 as determined by the U. S. Naval Observatory. This correction is extropolated, on a daily basis, to an accuracy of ±3 milliseconds. Actual corrections to ±1 millisecond are published in Naval Observatory Time Service Bulletins (ref. 87).

Because high frequency propagation is extremely variable (depending upon distance, time, reason, and other factors), most stations broadcast on several frequencies - including the six standard frequencies of 2.5, 5, 10, 15, 20, and 25 MHz. WWV is the only station broadcasting or all six. In general, the available signals from MSF, JJY, LOL-1, WWV, and WWVH provide coverage over most of the world.

The time signals broadcast from the five stations consist of time "ticks" corresponding to seconds of time. The WWV format is typical: the 1-second ticks, modulated on the carrier frequency, consist of 5 cycles of 1000-Hz sinewave, the start of which correspond to the second. When this "tick" is demodulated at a receiver, it produces a sound similar to the tick of a clock. If the audio output is presented on an oscilloscope, the "tick" can be seen and its timing measured to approximately 10 to 20 microseconds. This alignment function is integral to the calibration of the local clock.

C. SYSTEM ERROR ANALYSIS

The error budget for the synchronization system is made up of the following items:

- Transmitter synchronization errors
- Survey errors
- Propagation errors
- Receiving system errors
- Clock errors.

These will now be discussed in turn.

1. Transmitter Synchronization Errors

Transmitter synchronization errors are those associated with the maintenance of the time transmitted by the various stations relative to each other and relative to UTC. In this analysis it will be assumed that the discrepancy between UTC and other measurements of time are unimportant. In many cases synchronization to a particular standard such as UTC is also unimportant; but since some standard is necessary, it is desirable that it be a useful one.

Basically, the accuracy of time at the transmitting station depends upon the accuracy and stability of the frequency standard used, and upon the ability of BIH to measure the transmissions and communicate the data on their deviations. If, for example, a station uses a standard with a frequency error of 5×10^{-11}, this will give it a drift of 125 microseconds in a month. Then the extrapolation of a correction for a month will result in a maximum error of 0. 125 millisecond from this cause alone. The ability of BIH to measure time is essentially the same as that of any other clock suitably instrumented. The principal source of propagation error will be discussed later.

2. Survey Errors

The velocity of propagation is approximately 1000 feet per microsecond; that is, a survey error of 1 nautical mile (1 minute of longitude) produces an error of 6 microseconds. For this system a distance error of 10 nautical miles (60 microseconds) can be considered insignificant, thus the survey errors can generally be held to negligible values.

3. Propagation Errors

High frequency signals are propagated by reflection from the ionosphere, except at very short ranges (generally less than 100 miles)(ref. 35). Determination of the propagation time is a matter of determining the skywave path length. Reflections may take place from the E-layer, F-, or F2-layer - depending upon the distance, time of day, and condition of ionosphere. The E-layer, which is present only in daytime, has a virtual height of about 125 km, while the F-layer may be between 200 km and 450 km.

The maximum distance that can be spanned by a single hop via the F2-layer is about 4000 km. Thus, the dominant mode for any distance will be the number of hops equal to the next integer greater than the great-circle distance (in km) divided by 4000, as summarized in the following tabulation.

Distance (km)	Mode (No. of Hops)
0 to 4000	1
4000 to 8000	2
8000 to 12, 000	3
12, 000 to 16, 000	4

Morgan (ref. 82) has prepared a chart (figure 36) giving (to an accuracy of about 0. 1 millisecond) the propagation time for one-hop skywaves for virtual heights from 50 to 500 km. Once the distance, effective height, and number of hops have been determined, the graph of figure 36 can be used directly to determine propagation time. To calculate the time for an n-hop path, the distance is divided by n, next the delay is read from the graph, then the delay is multiplied by n. The graph also shows the error in delay produced by an error in estimating ionosphere height: approximately 0. 1 millisecond per hop at 3000 km. This variation in propagation time is shown in greater detail in figure 37 (also taken from Morgan), which shows the change in time, $\Delta t/n$, as a function of virtual height for several typical path lengths. The curve for dg/n when it equals 3000 km is also valid for 4000 km.

Another source of error is the making of a wrong guess as to the particular mode at distances where transitions between dominant modes will occur. For example, at 4000 km the one-hop mode, if present, has a propagation time (from figure 36) of 13.8 milliseconds. The two-hop mode propagation time is 2(7.2) or 14.4 milliseconds, a difference of 0.6 millisecond. A similar condition exists between two- and three-hop modes at 8000 km, where the difference in propagation time is also approximately 0.6 millisecond. This indicates the need, in certain cases, to identify the mode being used if maximum accuracy is desired.

On the other hand if 0.1-millisecond accuracy is not needed, then the simple propagation-delay curve of figure 38 can be drawn. This curve can be used to predict the propagation time, under normal conditions, to an accuracy of 1 millisecond. An "average" vertical height of 350 km provides sufficient accuracy at long ranges, as previously demonstrated.

Minimizing errors of propagation in clock synchronization can be accomplished by making measurements under stable conditions, maintained as nearly identical as possible from measurement to measurement. Adherence to the following rules should lead to the best results.

- Step 1: Choice of Frequency. The highest frequency below the MUF should be used. This value can be determined experimentally by checking the reception of signals or from the prediction of MUF, LUHF, or LRRP (lowest required radiated power), which can be determined from charts published by ITSA[5] (ref. 98).
- Step 2: Choice of Time-of-Day. Measurements should be made when the entire propagation path is either in complete daylight or in total darkness since these are the two periods of greatest stability of propagation time. Sunrise and sunset conditions can produce wide (and quite unpredictable) variations in signal amplitude and delay. Noon and midnight at the center of the path will generally provide the most stable environment for propagating the signals.
- Step 3: Choice of Mode. The lowest order mode which can be received is the one that will give the best results. Because it arrives first, the signal can be separated at the receiver and identified on a visual display. Because the length of the individual hops is the longest, the change in delay with variation of ionosphere height will be least, thereby giving the best accuracy of prediction.

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[5]The Institute for Telecommunication Sciences and Aeronautics (ITSA) is a division of the Environmental Science Services Administration (ESSA). These were formerly known as CRPL and NBS, respectively.

An indication of the ultimate accuracy obtainable using standard high-frequency time signals is provided by Morgan in an analysis of the synchronization of WWV and WWVH carried out in 1955. Over this 7687-km path the standard deviation of propagation times was found to be in the order of 0.25 millisecond. It is not to be expected that a typical field site would do as well; a standard deviation of twice that (0.5 millisecond) seems more reasonable as a value of propagation error.

4. Receiving System Errors

Receiving system errors consist of those errors contributed by the receiver and associated equipment being used to establish time synchronization of the receiving site. Delays in the receiver will be negligible if this unit is designed with a bandwidth in the order of 2 kHz.

The matching of the time tick on an oscilloscope is usually an operation that is performed manually - and which is, therefore, the greatest potential source of error in the receiver system. The ability to mark a point on the time tick is a function of the signal-to-noise ratio and the technique used for matching. In the case of the WWV time tick, time identification to one-tenth of a cycle denotes accuracy of 0.1 millisecond. In the presence of noise this accuracy is probably as good as can be expected, even using the persistence of the oscilloscope or photographic techniques to improve the match.

5. Clock Errors

The high-frequency radio synchronization method is well adapted to checking synchronization once per day - at the time of best propagation. It can be used with ordinary frequency standards, such as crystal oscillators, which exhibit some instability.

For the purposes of this discussion, clock errors are considered to be these errors caused by instability or calibration errors in the local frequency standard that accumulate between calibrations. The relationship between the characteristics of the standard and the time errors are straightforward.

Assuming that a standard with a functional frequency error of $\frac{\Delta f}{f}$ and an aging rate of a is being used, the time error, E, will be expressed by the relationship

$$E = E_o + \frac{\Delta f}{f} t + \frac{at^2}{2}$$

where E_o is the initial time error.

The clock error is related to the offset error, $\frac{\Delta f}{f}$, and the aging rate, a, for various time periods, as shown in figures 17 and 18. A good crystal frequency standard can be expected to have an aging rate in the order of 10^{-10} per day, so that with no frequency offset it would develop a 100-microsecond error in 5 days and a 1 millisecond error in 15 days. A frequency-offset error of 1 part in 10^9 will result in a 430-microsecond error in 5 days. These figures indicate that a time check every day or so is good enough to keep the clock error below 0.2 millisecond if a reasonably-good ($2000) crystal standard is used.

6. Errors of Coordination

If different stations are used to synchronize clocks around the world, then the accuracy of the coordination data from BIH and the stability of the individual stations involved must be considered. The magnitude of the errors to be expected may be estimated from the data supplied by BIH.

In calculating propagation time BIH uses the curve of figure 38 (a less-accurate method than that described by Morgan) which has a probable error in the order of 0.5 millisecond. Examination of a limited amount of data supplied by BIH covering the errors of the various coordinated signals indicates a month-to-month variation of only 0.1 to 0.2 millisecond in the average offset. It seems reasonable to expect then that UTC time can be obtained from any of the coordinated stations to an accuracy (at the station) of 0.5 millisecond or better.

D. METEOR SCATTER PROPAGATION

1. Introduction

It has been known for some time that meteors in passing through the upper atmosphere produce trails of ionization which reflect VHF signals. Such two-way meteor scatter communication has been demonstrated a number of times (refs. 35, 92, and 126), but this form of propagation is not widely used for communication because the meteors occur at irregular intervals, sometimes infrequently. However, its use has been proposed as a means of clock synchronization since the data rate requirements for synchronization are very low. Meteor scatter propagation has an advantage over some other modes of propagation in that its path is essentially discrete, with no multipath effects. The frequency used is high enough so that the propagation is the same in either direction; therefore, the paths can be considered reciprocal. Such two-way transmission can, therefore, be used as a measure of one-way propagation time to a high degree of accuracy.

2. Useful Coverage

The range of a meteor scatter system is limited to the line-of-sight range for the signal reflected from the trail in the ionosphere. Most ionized meteor trails occur at heights in the range from 80 to 120 km, thus limiting the range of the reflected signal to about 2000 km. Communication between transmitter and receiver occurs only while an ionized trail persists at a point between the two locations. The optimum location is not exactly halfway between the stations, but depends on the path direction and time of day. Since the optimum direction varies considerably over the diurnal cycle, antenna steering is required to obtain optimum coverage all day.

3. System Characteristics

Meteor scatter propagation is unique in that it occurs only during the short discrete times when ionization forms at the proper place in the upper atmosphere. The characteristics of meteors are such that the greatest number occur in the earth's atmosphere in the early morning, the actual number being quite variable. During certain times when the earth is passing through relatively dense clouds of meteorites, the frequency of occurrence is very high. At other times the frequency of occurrence may be low, but experimental evidence indicates that even on the poorest days dozens of trails occur that can provide communication between two points. Figures 39 and 40 from Davies (ref. 35) give the variation in the rates of observation of meteor bursts on a diurnal and a seasonal basis, respectively. The diurnal curve, figure 39, shows a maximum of 150 bursts per hour in the early part of the day (0300 to 0700 hours) and a minimum of about 30 per hour in the late afternoon and evening (1600 to 2200 hours).

The seasonal variation, shown in figure 40, indicates that the variation ranges from a minimum of 70 per day in February to a maximum of 275 per day in July. Obviously taken over a different path than that of figure 39, the rate is approximately one-half that of the previous figure for the month of May.

In any case, there are sufficient occurrences of meteor trails - even during February - to result in a number of two-way transmissions via this medium.

4. System Description

The meteor scatter synchronization system operates in a manner similar to that of other two-way transmission systems, with the one difference: the time of operation is random and generally unpredictable. The general mode of operation is as follows:

The Master station with its Master clock sends out a stream of pulses (e.g., 50 per second) via a directional antenna aimed at the expected reflection point. The transmitter is operating at a frequency of approximately 50 MHz at a 1-kw output power. The Slave station aims its directional receiving antenna at the reflection point, and adjusts its local clock generating pulses for a rate of 50 per second. When the Slave station receives a pulse via a meteor trail from the Master station, it immediately (after a fixed predetermined delay) sends back a pulse plus the next 50-pps pulse from its Slave clock. The meteor trail remains fixed in space long enough for the reply pulses to be sent back. Thus the Master station receives one pulse which measures the round-trip time and one pulse which gives the relative timing of the Slave clock. The Master station then communicates (via another channel, if desired) the correction required, if any, to the Slave clock. If the clocks are stable enough, the secondary communication channel could even be via ordinary mail facilities.

5. Accuracy of System

The meteor scatter synchronization system shares an advantage of other two-way transmission systems in that it is not necessary to know the exact location of either the Master or Slave station. Instead, the system accuracy depends upon the instrumentation and the stability of the meteor trail during synchronization.

There is no doubt that instrumental errors can be held to less than 0.1 microsecond by reasonable circuit design. Experimental evidence indicates that the stability of the reflection is such that fractional-microsecond timing can probably be achieved with this technique. This order of system accuracy has not been conclusively proven to date, but work now in progress under A. H. Morgan of NBS should provide reliable data on this subject within the year (ref. 82A).

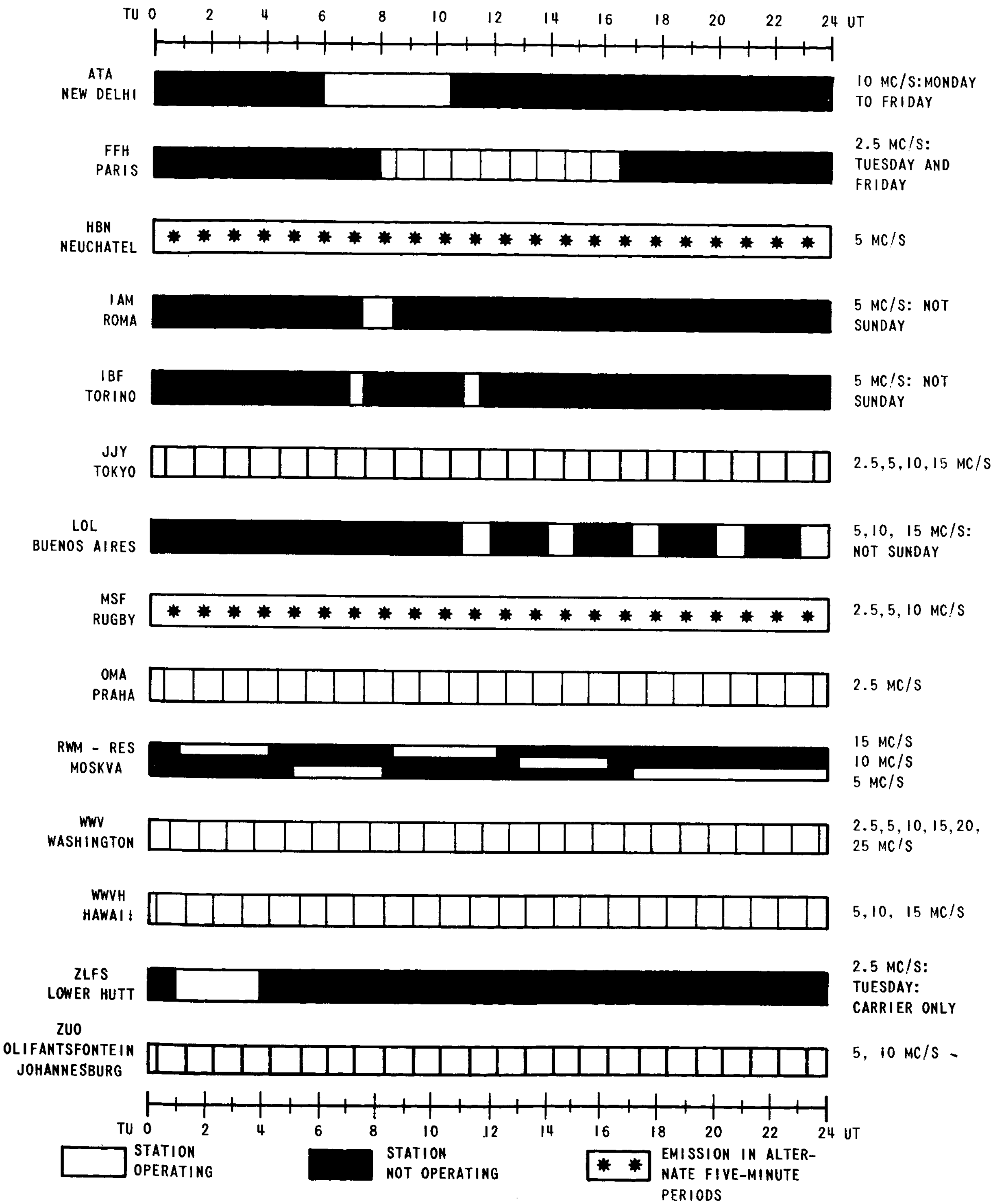

FIGURE 34. DAILY EMISSION SCHEDULE OF STANDARD TIME STATIONS

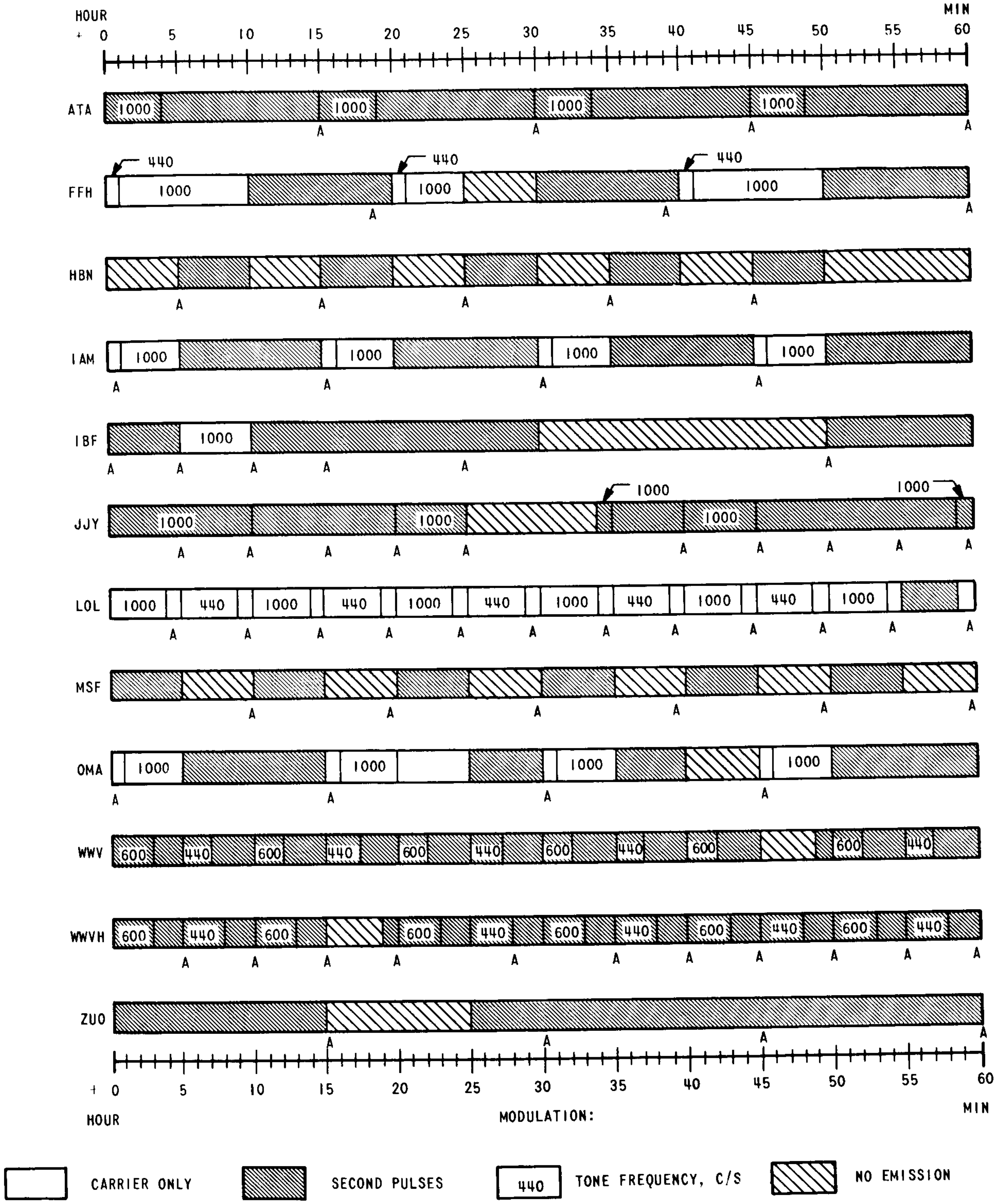

FIGURE 35. HOURLY MODULATION SCHEDULE OF STANDARD TIME STATIONS

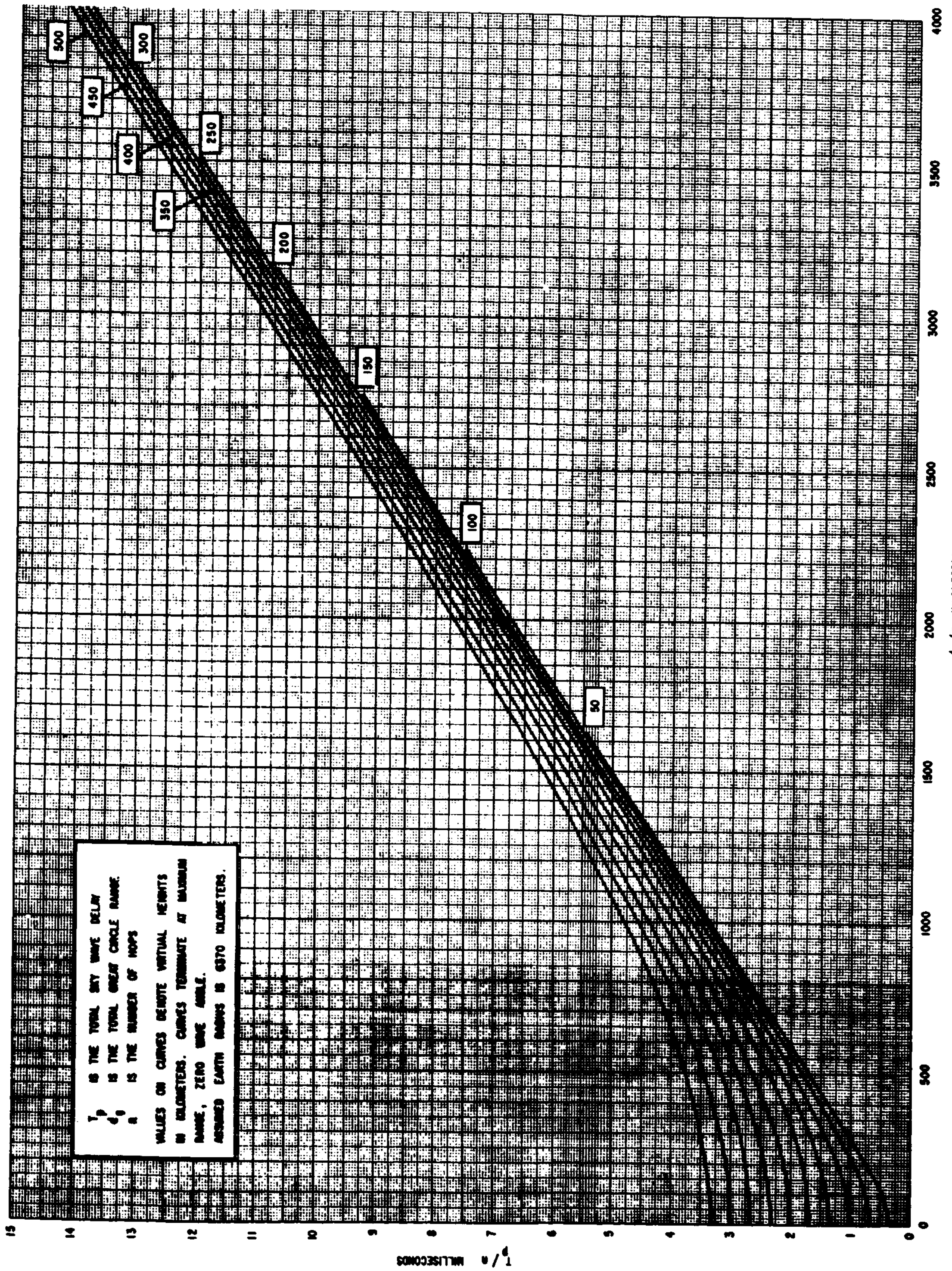

FIGURE 36. SKYWAVE PROPAGATION TIME VS RANGE

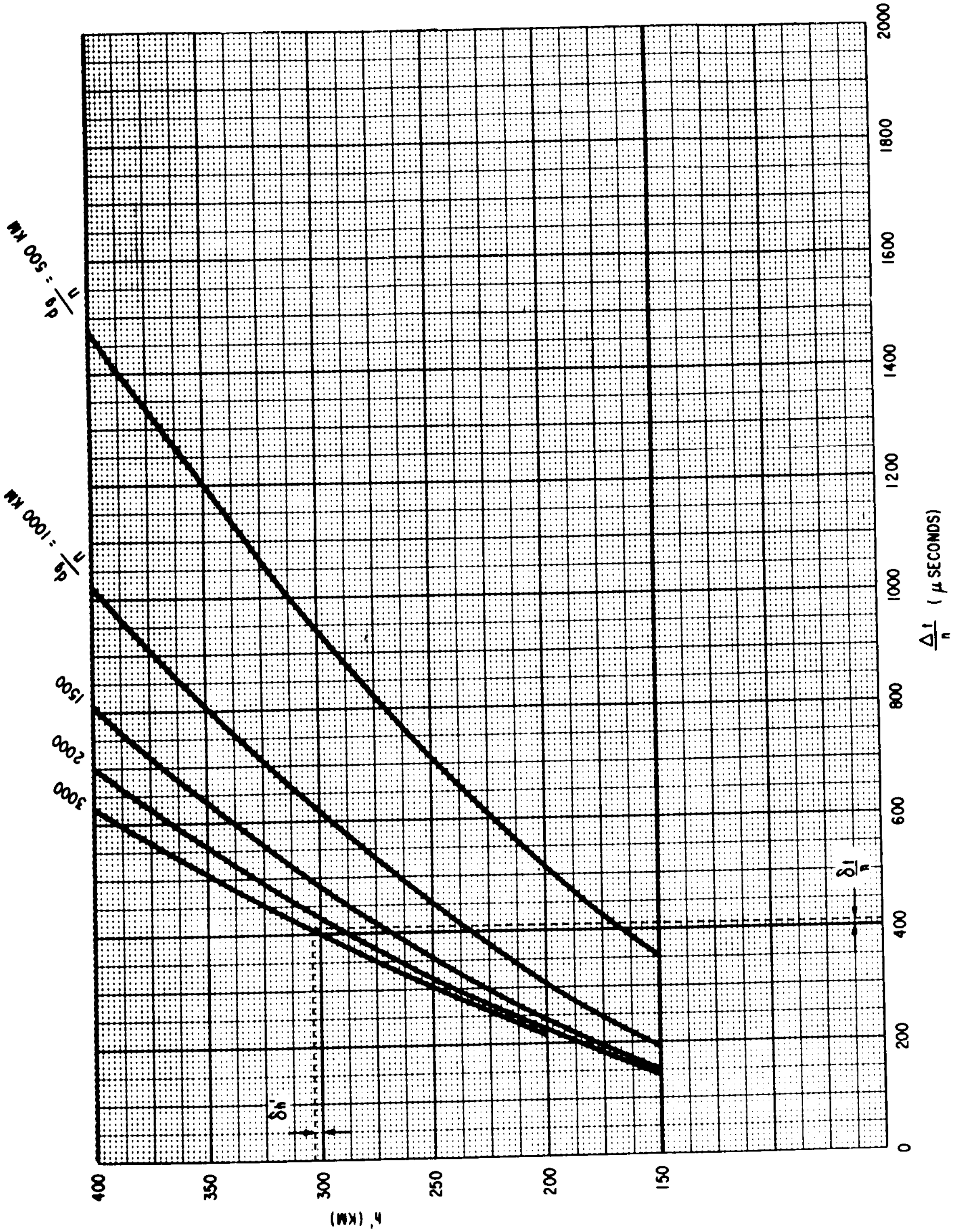

FIGURE 37. VARIATION OF PROPAGATION TIME VS VIRTUAL HEIGHT FOR TYPICAL PATH LENGTHS

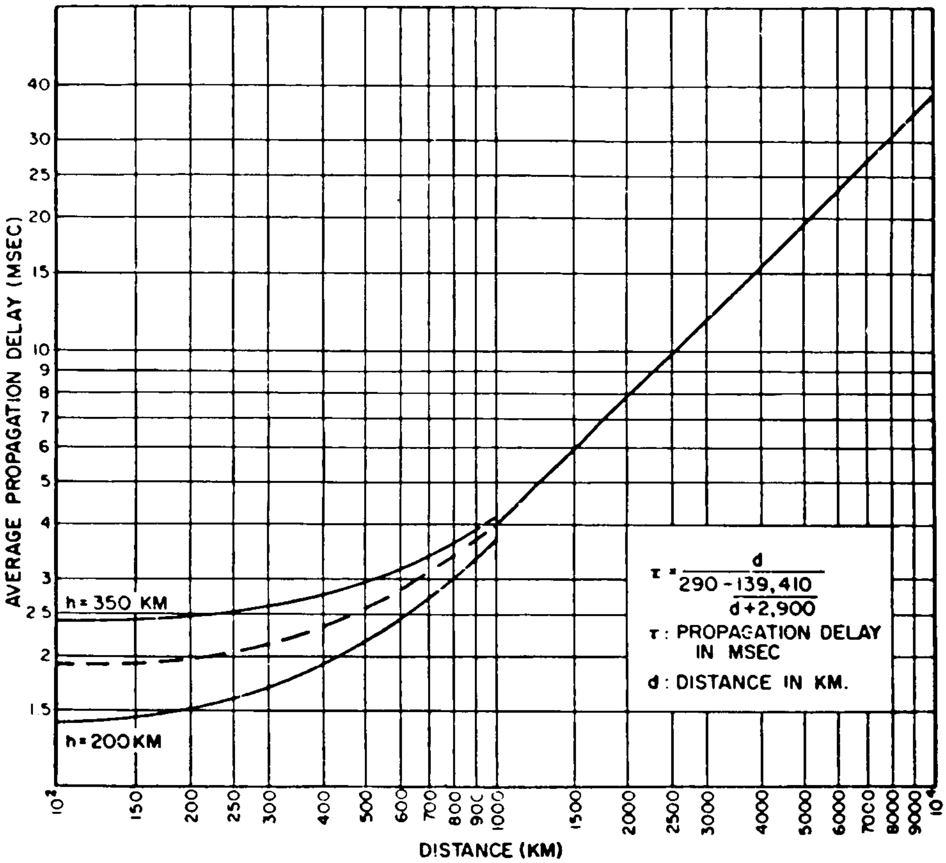

FIGURE 38. AVERAGE PROPAGATION DELAY VS RANGE AS USED BY BIH

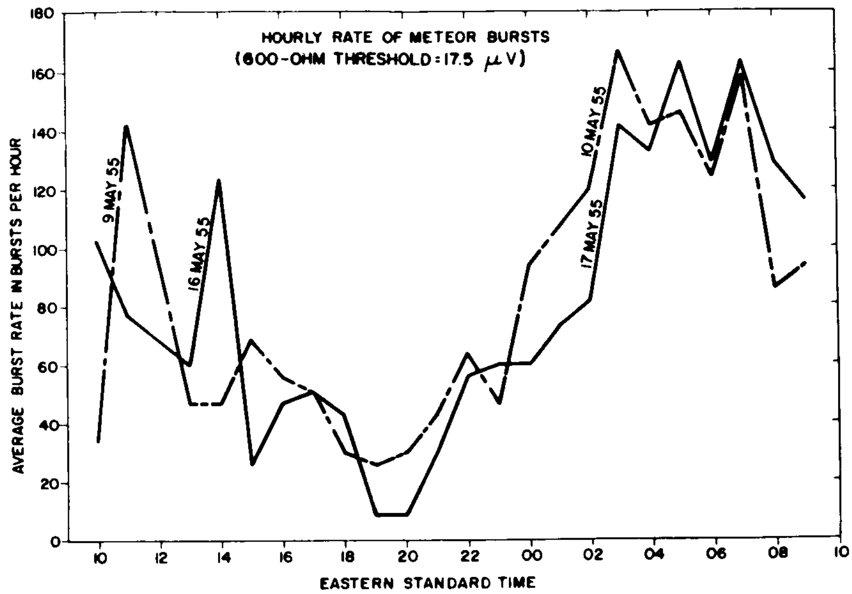

FIGURE 39. OBSERVED DIURNAL VARIATION OF METEOR BURST RATES, CEDAR RAPIDS-STERLING ON 49.8 MHZ

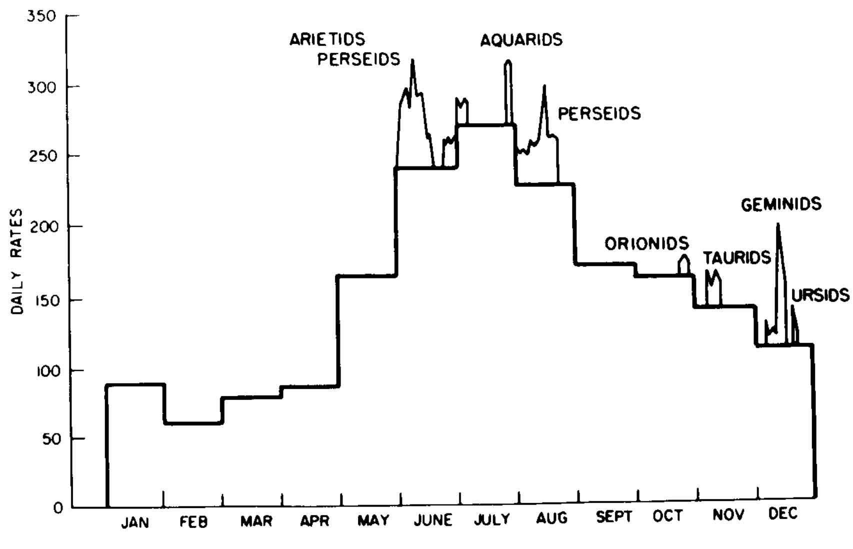

FIGURE 40. SEASONAL VARIATION OF METEOR RATES

SECTION IX

USE OF SATELLITES FOR CLOCK SYNCHRONIZATION

A. INTRODUCTION

Satellites carrying VHF and UHF transceivers are frequently capable of sending and receiving wideband signals to and from stations over wide areas of the earth. Within line-of-sight of the satellite, pulses with microsecond time resolution or a variety of cw signals can be sent and received to provide time information.

This section discusses the two general classes of satellites; active and passive, usedfor achieving clock synchronization. "Active" satellites are those (such as GEOS-A) carrying a clock on board, which permits their use as a time reference by ground stations. "Passive" satellites (such as TELSTAR and RELAY) act as convenient relay points for distribution of time signals from one ground station to another.

B. COVERAGE AVAILABLE

The area of the earth served by an active or a passive satellite depends upon the particular orbit in which it has been placed; that is; the satellite's orbit must be such that it will appear, at sufficiently frequent intervals, within sight of each station it is required to serve. A polar orbit will give world-wide coverage, but if the orbital plane intersects the equatorial plane at an angle other than 90 degrees, the satellite will not pass over the poles. Moreover, if the ray path from the ground station to the satellite is too close to the horizon, excessive atmospheric attenuation and refraction will occur. The minimum useful elevation is generally taken to be 15 degrees.

The great circle distance, D, from the subsatellite point to a ground station as a function of minimum elevation angle, α, is given by equation (1)[6]

$$D = R \arc\cos \left(\frac{\cos^2 \alpha}{K} + \sin \alpha \sqrt{\frac{1 - \cos^2}{K^2}} \right) \tag{1}$$

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[6]Refer to the glossary of table 21 for definitions of all terms used in Section IX.

Great circle distance is plotted against normalized orbital radius K for various values of elevation angle α in figures 41 and 42, while figure 43 converts altitude in miles to K. The relationships shown in these figures reveal that, at any time, the satellite covers a circle D miles in radius which generally moves across the earth as a band 2D miles wide. Any ground station within this band will receive signals from the satellite on at least one pass, and two stations within the circle can use the satellite as a relay.

For example, for GEOS-A with an average altitude of 700 nm (K equals 1.2), an elevation angle of 15 degrees gives a coverage circle with a radius D of 1325 nm.

Because the earth is rotating beneath the satellite, the longitude at which the orbit of the satellite crosses a particular latitude will appear to shift by an amount given by

$$\Delta\lambda = \frac{P}{24} \, 360 \text{ deg} \tag{2}$$

where P is the orbital period in hours and is given by

$$P = 2\pi \sqrt{\frac{R}{g}} \quad K^{\left(\frac{3}{2}\right)} \tag{3}$$

P is plotted as a function of K in figure 44.

Translated into distances, this means that the orbit of the satellite will cross a specific latitude, ϕ, shifted by a distance, d (given by equation 4), after each revolution.

$$d = \Delta\lambda \cos \phi \tag{4}$$

In the preceding equation if $\Delta\lambda$ is expressed in minutes, d will be in nautical miles. When K is 1.2, P equals 1.8, and $\Delta\lambda$ equals 27 degrees. At the equator, d is 1620 nautical miles.

The overlap of two successive passes (i.e., the width of the band which can see the satellite twice) is given by the expression

$$W = \frac{2D}{\sin\theta} - d \tag{5}$$

For GEOS A with D equal to 1325, d equal to 1620, and θ equal to 60 degrees, W equals 1440 nautical miles on the equator; that is, nearly all ground points will see the satellite on two successive passes.

The subsatellite plot of the first six orbits of GEOS A is illustrated in figure 45, which shows the coverage belt given by the superimposition of the first two orbits. From this plot it can be seen that the entire surface of the earth between 81 degrees N latitude and 81 degrees S latitude is covered. The average time between passes is less than 12 hours.

A satellite in an orbit where K is equal to 1.5 would have a period of 2.4 hours; a $\Delta\lambda$ of 36 degrees; and a coverage radius, D, of 2150 nautical miles. At the equator the latitude shift, d, would be 2160 nautical miles - giving complete overlap.

C. SATELLITE POSITION

A satellite's position can be described in terms of its Keplerian orbital elements and some initial conditions. Using this data, the nominal position of the satellite can be calculated at any time in the future.

To obtain orbital information from raw data collected by the tracking systems, the normal procedure is to feed the data into a computer which rejects data points that are obviously in error, smooths the remaining data, and performs the necessary computations.

Because such factors as atmospheric drag, the earth's oblateness, and the effects of the sun and moon are not taken into account sufficiently in Kepler's equations, they are not complete enough for accurate determination of the satellite's position. For example, in a near orbit the oblateness term dominates. If this were neglected, a satellite in a 100-mile altitude, near-polar orbit would accumulate an error of 5.9 nautical miles per orbit, while an error of 27 nautical miles per orbit is typical for a satellite in a 200-mile altitude orbit at a 30-degree inclination. If the second-order oblateness terms are neglected, the error will be 100 feet per orbit and 252 feet per orbit, respectively.

For a near orbit the effects of atmospheric drag are also strong and can be predicted on a first-order basis, but drag fluctuates in a random manner. A 33-percent increase in atmospheric drag will result in an error of 0.05 nm in the predicted orbital radius of a 200-mile altitude satellite after 10 hours, and in the same period an error of more than 0.1 nm in the subsatellite point position (ref. 79).

The occurrence of these errors means that the computer program must be sufficiently complex to handle high-order perturbation terms. In addition, the information must be periodically updated to account for the unpredictable nature of atmospheric drag. In order to maintain reasonable accuracy, the satellite's orbital information should be updated at intervals ranging from one day to one week. This information could then be distributed, using either the satellite itself or some other type of data link as a communications medium.

On a single-pass basis, the satellite's position can be expected to be known to approximately 0.1 mile.

D. PASSIVE SATELLITE (No On-Board Clock)

1. One-Way Transmission

a. Introduction

This method for obtaining clock synchronization consists of transmitting time signals to various Slave stations from a Master station using high-frequency radio transmissions relayed by a satellite. Here, the assumption is made that the position of the satellite relative to the earth at the time of the transmission is known, and that the positions of the Master and Slave stations on the earth are also known. Under these conditions, then, the propagation path length (and, therefore, the transmission delay) can be calculated. This method has two advantages: the Slave stations require no transmitting equipment, and the satellite can be merely a rebroadcaster.

The disadvantages of this method are that the orbital parameters of the satellite must be distributed and periodically updated to account for various perturbations in the orbit. The Slave stations must have computing equipment to translate the received orbital data into meaningful path-length information, or path lengths must be computed by a central computer. Also since this is an "open loop" system, errors which might occur may go undetected.

b. Coverage

The coverage obtained by using this method is limited by the area of the coverage circle defined by the satellite (as described in paragraph IX. B) and by the nature of the orbit. For a satellite in the GEOS-A orbit, for example, the maximum distance of 2650 nm (for 2D) between stations can be achieved only when the satellite is halfway between the stations. A distance of approximately half the maximum, 1325 nm, can be spanned approximately twice per day. A satellite with a normalized orbital radius of 1.5 can span about 2500 nm with slightly less frequency.

c. Accuracy

The error budget for this system consists of the following sources of error:

- Satellite position error
- Receiving station position error
- Propagation error
- Equipment delay error
- Clock error.

These will now be discussed and evaluated in turn.

(1) Satellite Position Error

Techniques for determining satellite position were previously discussed in paragraph IX. C where it was noted that time is only one input to position error, since consideration must be given to factors such as atmospheric drag, oblateness of the earth, effects of sun and moon, etc. It is assumed that the station using the satellite for timing will, for other reasons, have access to tracking information and a computer for reducing the data.

In order for a station to determine the satellite's position from the orbital information, it must also know the correct time. At worst, however, time will be known to a millisecond, which is equivalent to approximately 20 feet of satellite position at typical velocities. Thus, this portion of position error can, in general, be neglected.

Some reduction in timing error can be obtained by using the time of minimum propagation delay between the transmitter and receiver as the time for achieving synchronization. The time of minimum propagation delay can be determined by a doppler technique which either compares the frequency of a signal transmitted from one station to the other against a standard frequency at the receiving station or which measures the time between the reception of the transmitted timing marks. In each case the time of zero doppler is the time of minimum propagation delay. The major advantage of this method is that any error in the determination of the satellite's position lying along the satellite's path does not affect the accuracy of the timing.

Including all sources of error, a typical propagation-path length error due to uncertainty of the position of the satellite is in the order of ± 500 feet. This position error will result in a timing error of ± 0. 5 microsecond.

(2) Receiving Station Position Error

Not only is it important that the satellite's position be accurately known, but it is equally important that the position of each ground station also be accurately established. Currently, ground positions are not known to accuracies any better than 100 feet. Typical inaccuracies over much of the United States and Europe are in the order of 150 feet (50 meters), and in some parts of the world uncertainties of more than 1000 feet are common. However, stations equipped to receive time signals from satellites will generally be in the more-accurately surveyed areas. If it is assumed that the total propagation-path length error caused by the uncertainty in the ground position is in the order of 100 ft, the timing error attributable to this factor will be ± 0. 1 microsecond.

Station position errors using signals from geodetic satellites are expected to be reduced to ± 30 ft (10 meters) by 1968 according to E. V. Hobbs, Assistant Project Manager for GEOS.

(3) Propagation Errors

Once the path length is determined the propagation delay from one ground station to another can be found by dividing the total distance by the velocity of propagation. The accepted value of the speed of light in free space is 299,792.5 ± 0.3 km/sec. The uncertainty associated with this velocity is negligible in the presence of the other sources of timing error.

The velocity of propagation will change from its nominal free space value when passing through the earth's atmosphere and ionosphere. The index of refraction of the atmosphere drops in an exponential manner from a value of about 1.0003 at sea level to a value of about 1.00003 at an altitude of 10 miles. If, as an approximation, one assumes a 5-mile-thick layer with μ equal to 1.0003, a ray at an elevation of 15 degrees will pass through less than 5/sin 15 degrees (equivalent to 20 miles) at each end. Since the ray takes 200 microseconds to traverse the atmosphere at both ends, the delay introduced by atmospheric refraction will be less than 200 x 0.0003 or 0.06 microsecond. This amount of time delay will generally be negligible.

The index of refraction of the ionosphere is not a constant, but is a function of frequency. At frequencies greater than 500 MHz the ionospheric refraction is negligible, but at lower frequencies it must be taken into account and at frequencies in the vicinity of MHz it dominates.

The one-way group path delay for a 100-MHz signal is typically 1.3 microseconds (ref. 72). The delay for other frequencies can be found by noting that the index of refraction - and, therefore, the delay - is inversely proportional to the square of the frequency. The deviation of propagation time from the nominal free-space propagation time for one passage through the ionosphere is given as a function of frequency in figure 46.

The error incurred by neglecting the effects of ionospheric refraction is negligible for frequencies above 500 MHz; however, at lower frequencies, correction factors in accordance with the data of figure 46 will have to be applied to both the up-path and the down-path. The delay will vary with the particular angle at which the ray path passes through the ionosphere and with the electron density. Typical errors for frequencies between 100 and 500 MHz will be 0.5 microsecond.

(4) Equipment Delay Errors

A potential source of error is uncertainty in equipment delay at each ground station and at the satellite. The accuracy to which these delays can be measured depends upon the techniques used. If reasonable care is taken, the equipment delays should be measureable to within 0.2 microsecond.

At the receiving station periodic delay calibrations can be made by using a signal simulator that transmits accurately timed rf pulses into the receiving antenna.

(5) Clock Error

Because of the limited coverage available from a single satellite it may be difficult to check time synchronization more often than once a day. It is, therefore, necessary to use highly stable clocks to maintain time synchronization between checks.

If crystal oscillators are used as the frequency standard for the clock, the time error can be expressed as

$$E = E_o + \frac{\Delta f}{f} t + \frac{a}{2} t^2$$

where E_o is the initial time error, $\Delta f/f$ is the initial frequency offset, and a is the aging rate. A typical frequency offset of 1 part in 10^{10} will result in an 8.64-microsecond error after 1 day, and an aging rate of 1 part in 10^{10} will result in a 4.32-microsecond error in the same period.

The aging rate of the best available crystal oscillators will stabilize at about 1 part in 1011 per day. Therefore the clock error will depend principally upon the ability to set, or measure, the frequency of the standard.

An atomic standard, set to one part in 10^{11} and with negligible aging rate, will accumulate less than 1 microsecond of time error per day.

2. Two-Way Transmission

a. Introduction

The use of one-way transmission with passive satellites for obtaining clock synchronization involves errors associated with the uncertainty of satellite and ground station positions, and with variations in propagation velocity, as previously described. These uncertainties can be virtually eliminated by using techniques that measure the round-trip transmission time between satellite and ground station - which can be done at the expense of installing round-trip transmitting and receiving equipment at both ground station and satellite.

b. Coverage

The requirement for coverage from a satellite using two-way transmission is the same as for one-way transmission: that is, both ground stations must be within the coverage circle at the same time. The discussion in para. IX.D.1.b applies equally to most of this paragraph. These parameters are given in figures 41 and 42 in which great circle distance D is plotted against normalized orbital radius K for various values of elevation angle α. Altitude in miles is converted to K in figure 43.

c. Accuracy

The error budget for two-way transmission consists of the following three sources:

- Equipment delay error
- Satellite motion error
- Clock error.

These will now be discussed and evaluated in turn.

(1) Equipment Delay Error

In an example of this method a path-length-determination (PLD) pulse is transmitted from a ground station to the satellite, where it is retransmitted. A second station receives the PLD pulse from the satellite and immediately transmits a second pulse which returns to the first station over a nearly identical path via the satellite.

The total time delay between the transmission of the PLD pulse and the reception of the returned pulse is expressed by the relationship

$$\Delta t = 2R + \delta_{1T} + \delta_{1R} + \delta_{2R} + \delta_{2T} \qquad (7)$$

where R is the total travel time from ground transmitter to receiver, including the retransmission delay in the satellite.

The delay time from the second transmitter to the first can be found by rearranging the terms in equation (7) so that

$$T = R + \delta_{2T} + \delta_{1R} = \frac{\Delta t}{2} + \frac{(\delta_{2T} - \delta_{1T}) - (\delta_{2R} - \delta_{1R})}{2} \qquad (8)$$

If the transmitting and receiving equipments used for the two stations have equal delays (i. e., if δ_{1T} is equal to δ_{1R} and δ_{2R} is equal to δ_{2R}), the transmitting and receiving delays cancel. In this case

$$T = \frac{\Delta t}{2} \tag{9}$$

If the delays are not equal, the transmitting and receiving delays must be measured and then used in equation (7). In any case, it should be possible to compute T to within 0.2 microsecond.

A clock synchronization pulse can be transmitted from the second station close to the time that the PLD pulse was transmitted. Known delay T (total of propagation time delay and equipment delay) can now be subtracted from the time this pulse is received at the first station, and close synchronization between the two stations can thereby be obtained.

The timing pulse can be used as the range determination pulse in the following manner: Station A transmits to Station B via the satellite, which notes the time of arrival and immediately retransmits back to Station A over the same path. Station A then computes the propagation time and sends this information to Station B which then corrects the time of arrival data and sets its clock. The disadvantage of this system is that a secondary communication link must be established.

An alternate to this method is that each station transmits a timing pulse and measures the difference between the time it transmits and the time that the transmitter pulse from the other station is received; i. e.,

$$\begin{aligned} H_{AB} &= (t_B - t_A) + R + \delta_{AT} + \delta_{BR} \\ H_{AB} &= (t_A - t_B) + R + \delta_{BT} + \delta_{AR} \end{aligned} \tag{10}$$

Subtraction then yields

$$(t_a - t_b) = \frac{H_{BA} - H_{AB}}{2} + \frac{(\delta_{BR} - \delta_{AR}) - (\delta_{BT} - \delta_{AT})}{2}$$

if

$$\frac{(\delta_{BR} - \delta_{AR}) - (\delta_{BT} - \delta_{AT})}{2} = 0$$

and

$$t_A - t_B = \frac{H_{BA} - H_{AB}}{2}$$

By employing this technique, W. Markowitz of the U. S. Naval Observatory (August 1962, using Telstar) was able to achieve time synchronization between Andover, Me., and Goonhilly Downs, Cornwall, U. K., to within 1 microsecond (ref. 113).

A similar experiment was carried out in 1965 using Relay II to transmit pulses between the NASA Mojave Tracking Station and Kashima, Japan (ref. 79). Overall synchronization accuracies in the order of a few tenths of a microsecond were achieved.

If stations trying to synchronize to each other both have range-determining satellite tracking systems (such as optical laser systems, Goddard Range and Range Rate, or SECOR), then the propagation path length from each station to the satellite can be accurately determined. A secondary transponder channel can then be used for transmission of the timing pulse. To avoid the problem of propagation anomalies caused by ionospheric refraction, the secondary transponder channel should use a carrier frequency as close as possible to that of the tracking system.

(2) Satellite Motion Error

One source of error is the motion of the satellite during the period that the propagation delay time is being determined. For a two-way trip, the delay between the time the satellite's transponder is used for the forward path and the time it is used for the return path may be in the order of 30 milliseconds for a 1000-nm altitude orbit. The velocity, V, of a satellite in a circular orbit can be found from the relationship

$$V = \sqrt{\frac{g\,R}{K}} \tag{13}$$

Satellite velocity is plotted against K in figure 47.

For an altitude of 1000 nm (K equal to 1.29), V equals 23,000 ft/sec. The rate-of-change of the path length from a ground station to the satellite is the component of the velocity vector lying along the line-of-sight between the two objects. The maximum rate-of-change of path length occurs when the satellite is on the horizon and traveling either directly toward or away from the observer. The rate-of-change, $\dot{r}$, of path length r at this time is given by the relationship

$$\dot{r} = \frac{V}{K} \tag{14}$$

The value of $\dot{r}$ for an orbit with an altitude of 1000 nm is approximately 18,000 ft/sec. The path length between a ground station and the satellite can, therefore, change by as much as 540 feet during the 30 milliseconds necessary to propagate the timing pulse from the satellite to the ground station and back to the satellite. This difference in path length represents a change in propagation time between the two of 0.54 microsecond. This error can be made negligibly small if the time of zero doppler (minimum propagation delay) is used for synchronization. The error is negligible for most applications if the timing pulse is transmitted within a few milliseconds of the range determination pulse.

(3) Clock Error

Since the coverage problem for the one-way transmission method is the same as that for the two-way method, the errors attributable to clock instability are the same. The discussion of clock error previously given in para. D. 1. c. (5) of this section applies equally here.

E. ACTIVE SATELLITE (On-Board Clock)

1. Description

The clock synchronization method using an active satellite involves mounting within the satellite a stable clock that is used as the basis for time signal transmissions from the satellite to the ground. The one-way propagation delay can be calculated in a manner similar to that already described in this section in para. D. 1. c. (3). An advantage of the active satellite is that, since it need be visible from only one station at a time, one satellite can provide world-wide coverage. However, a disadvantage of this system is that the on-board clock must be corrected periodically to compensate for oscillator instability, or that correction factors must be determined and distributed to the ground station to correct the received time data.

For example, the clock on board the GEOS-A satellite consists of a quartz crystal oscillator that is divided down to slightly more than one pulse per minute. The rate is corrected to exactly one pulse per minute by deleting a certain number of pulses every minute from the output of the divider stages. Each deleted pulse corrects the time between the minute marks by 98 microseconds.

The amount of correction required is determined by a ground station which periodically updates the data in the memory of the satellite. This information causes pulses to be deleted at a rate of from zero to 236 pulses per minute. Fine correction is obtained from the normalizer vernier word, which deletes pulses at a rate of from one pulse in 2 minutes to one pulse in 2^{10} minutes.

The minute marks are transmitted to the ground stations on a carrier which is phase modulated by a train of squarewaves lasting about one-third of a second and having a phase reversal near the end of the train, as shown in figure 48. This format is used because of the narrowband equipment necessary for receiving signals from the satellite's low power transmitter. In order to get reasonable resolution, synchronous detection on a repetitive signal (the squarewave) is necessary. If a high-power, wideband system is used, better resolution with a simpler format is possible.

2. Coverage

To obtain satisfactory coverage from an active satellite it is required that the satellite be visible from the ground station above the minimum elevation angle. A discussion on the frequency of useful passes, equally applicable here, is given in paragraph B of this section of the report.

3. Accuracy

As with the passive satellite, there are two ways to determine the propagation delay: One is to calculate the path length and then the one-way propagation delay; the other is to use two-way radio propagation data.

For one-way propagation, the error budget consists of the following sources:

- Satellite position error
- Ground station position error
- Propagation error
- Equipment delay error
- Clock error.

For two-way propagation, the error budget consists of the following sources:

- Equipment delay error
- Satellite motion error
- Clock error.

These will now be discussed and evaluated in turn.

a. One-Way Propagation

(1) Satellite Position Error

The error caused by uncertainty in the position of the satellite will result in errors of the same order as previously described in paragraph D.1.c of this section. If the time that the satellite is closest to the ground station (zero doppler) is used as the time to effect synchronization, the component of the position error along the path of the satellite can be neglected. If the uncertainty in the component of position error along the station-to-satellite path is 500 ft , the average timing error will be approximately 0.5 microsecond.

(2) Ground Station Position Error

As described in paragraph IX. D. 1. c. (2), the ground station position may have an uncertainty of 150 ft (50 meters) which will introduce a timing error of less than 0.15 microsecond.

(3) Propagation Error

In one-way transmission, the effects of atmospheric and ionospheric refraction are the same for an active satellite as they are for a passive satellite, except that the propagation path of the active satellite traverses the atmosphere and ionosphere only once. As described in paragraph D. 1. c. (3) of the section, the amount of error - which depends upon the frequency of the carrier used - can range from no error at all to errors in the order of a microsecond. An error of 0.3 microsecond can be considered to be representative at 200 MHz.

(4) Equipment Delay Error

Any error in knowing the delay within the equipment will result in a similar error in the timing accuracy. The equipment delay should be measurable to within 0.2 microsecond.

(5) Clock Error

The only source of error possessed by an active satellite system but not by a passive satellite system is the error caused by the instability of the satellite's clock. The error, E, resulting from this instability can be broken into three components as expressed in the relationship

$$E = E_o + \left(\frac{\Delta f}{f}\right) t + \frac{at^2}{2} \qquad (15)$$

If only synchronization between clocks is desired and it is not important that the clock conform to an accepted time scale, such as UT2 or A. 1, the E_o term can be eliminated from the preceding equation since it will be a constant added to each clock. The error between two clocks can be given by

$$E = \left(\frac{\Delta f}{f}\right) t + \frac{at^2}{2} \qquad (16)$$

where t is the time between the setting of the first clock and the setting of the second, $(\Delta f/f)$ is the drift rate of the time error at the time that the first clock is set, and a is the time error acceleration. Since no more than 12 hours will have to elapse between the setting of the two clocks, the term $(at^2/2)$ will generally be negligible.

The error between clocks is, therefore, given by

$$E = \left(\frac{\Delta f}{f}\right) t \tag{17}$$

For a crystal oscillator, the $(\Delta f/f)$ term can generally be set to no better than a few parts in 10^{10}. An error of one part in 10^{10} will result in an error of 4.3 microseconds after 12 hours.

Although the oscillator frequency drift is negligible for a short-term, time-error calculation, it must be taken into account over a long period. Because of crystal aging, the $\Delta f/f$ term will increase at a rate of about five parts in 10^{10} per day initially, and after long periods of operation it may increase less than one part in 10^{10} per day; that is, after a few days $(\Delta f/f)$ will build up to several parts in 10^9, and large errors on the order of 50 microseconds for a 12-hour period will result unless the drift is corrected or information about the drift rate is distributed.

If an oscillator-frequency correcting scheme (such as that of the GEOS satellite) is used, an additional error associated with the resolution of the correction will occur. Since each deleted pulse causes a correction of 9.8 microseconds, an error of this magnitude may be introduced between two stations using the satellite if one station should synchronize immediately before the vernier correction pulse and one station immediately after. However, this type of error can be reduced considerably since more-precise correction methods are available - such as the use of a four-phase gate on the primary oscillator output with which each correction pulse will advance or retard the oscillator phase by one-half of a period of the primary frequency. With a 5-MHz oscillator, the corrections will be in steps of 0.1 microsecond.

If an atomic frequency standard is used in the satellite, these problems can be avoided and clock accuracy to within approximately 0.2 microsecond is achievable. Such standards have not been used to date because they are larger and heavier, and consume more power than quartz oscillators.

The problem of ground clock instability is less for active satellites than for passive satellites because of the greater frequency of time fixes that are available. Using an atomic standard, this error will be on the order of 0.2 microsecond.

b. Two-Way Propagation

(1) Equipment Delay Error

It should be hypothetically possible to reduce the one-way propagation errors just discussed in paragraph E.3.a by the use of round-trip data. In such a hypothetical system, a pulse is transmitted from a ground station to the satellite, from which it is then retransmitted back to the ground station. The total time delay is given by the expression

$$\Delta t = 2R + \delta_T + \delta_R + \delta_S \tag{18}$$

If the correct time is defined as the instant that the timing pulse is transmitted from the satellite, the total propagation delay can be given by

$$T = R + \delta_R \tag{19}$$

Combining equations (18) and (19) yields the relationship

$$T = \frac{1}{2} (\Delta t + \delta_R - \delta_T - \delta_S)$$

Since Δt is known, the accuracy to which T can be obtained depends upon the accuracy to which δ_R, δ_T, and δ_S are known. These values should be measurable to within 0.2 microsecond.

(2) Satellite Motion Error

Since the satellite is moving during the period that the propagation delay is being determined, the timing pulse from the satellite must be transmitted within a few milliseconds of the time that the PLD pulse arrives at the satellite. The magnitude of the error to be expected because of this effect is discussed in paragraph D. 2. c. (2) (p. 160). This error can be held to a negligible amount.

F. ERROR ANALYSIS

The error sources and their respective errors were analyzed for both passive and active satellites operating under one- and two-way transmitting conditions. The root-sum-square (RSS) error computed for each of these four cases showed that the errors for the active type of satellite were 0.3 microsecond less then the corresponding error for the passive type of satellite. The breakdown of this data is given in the following tables 17, 18, 19, and 20.

TABLE 17. ERROR ANALYSIS SUMMARY FOR ONE-WAY TRANSMISSION OF PASSIVE SATELLITE

Source of Error		Amount of Error (μsec)
Satellite Position		0.5
Receiving Station Position		0.15
Propagation (100 to 500 MHz)		0.5
Equipment Delay		0.2
Clock (Atomic Oscillator)		0.5
	RSS Error:	0.9 μsec

TABLE 18. ERROR ANALYSIS SUMMARY FOR TWO-WAY TRANSMISSION OF PASSIVE SATELLITE

Source of Error		Amount of Error (μsec)
Equipment Delay		0.2
Satellite Motion		(Can be made negligible)
Clock		0.5
	RSS Error:	0.6 μsec

TABLE 19. ERROR ANALYSIS SUMMARY FOR ONE-WAY TRANSMISSION OF ACTIVE SATELLITE

Source of Error		Amount of Error (μsec)
Satellite Position		0.5
Ground Station Position		0.15
Propagation		0.3
Equipment Delay		0.2
Clock - Satellite		0.2
- Ground		0.2
	RSS Error:	0.7 μsec

TABLE 20. ERROR ANALYSIS SUMMARY FOR TWO-WAY TRANSMISSION OF ACTIVE SATELLITE

Source of Error		Amount of Error (μsec)
Equipment Delay		0.2
Satellite Motion		(Can be made negligible)
Clock - Satellite		0.2
- Ground		0.2
	RSS Error:	0.3 μsec

TABLE 21. GLOSSARY OF TERMS FOR SATELLITE CLOCK SYNCHRONIZATION

Notation	Definition of Term
a	Linear Frequency Drift Rate
c	Velocity of Light
D	Distance Along Surface of Earth
d	Longitude Displacement of Successive Orbits
E	Error
f	Frequency
g	Acceleration of Gravity
H_{AB}	Time between Transmission for A and Receipt of Pulse from B
K	Normalized Orbital Radius
dl	Elementary Path Length
N	Electron Density
P	Orbital Period
R	Radius of Earth
R	Radio Propagation Time
r	Path Length
$\dot{r}$	Rate-of-Change
S	Surface Area
S_T	Total Surface Area of Earth
T	Total Delay
t	Time
Δt	Time between Transmission and Receipt of Return Pulse
V	Velocity
W	Coverage-Band Overlap Width
α	Elevation Angle to Satellite
δ	Equipment Delay
θ	Inclination of Orbit
λ	Longitude
μ	Index of Refraction
φ	Latitude
ω	$2\pi f$

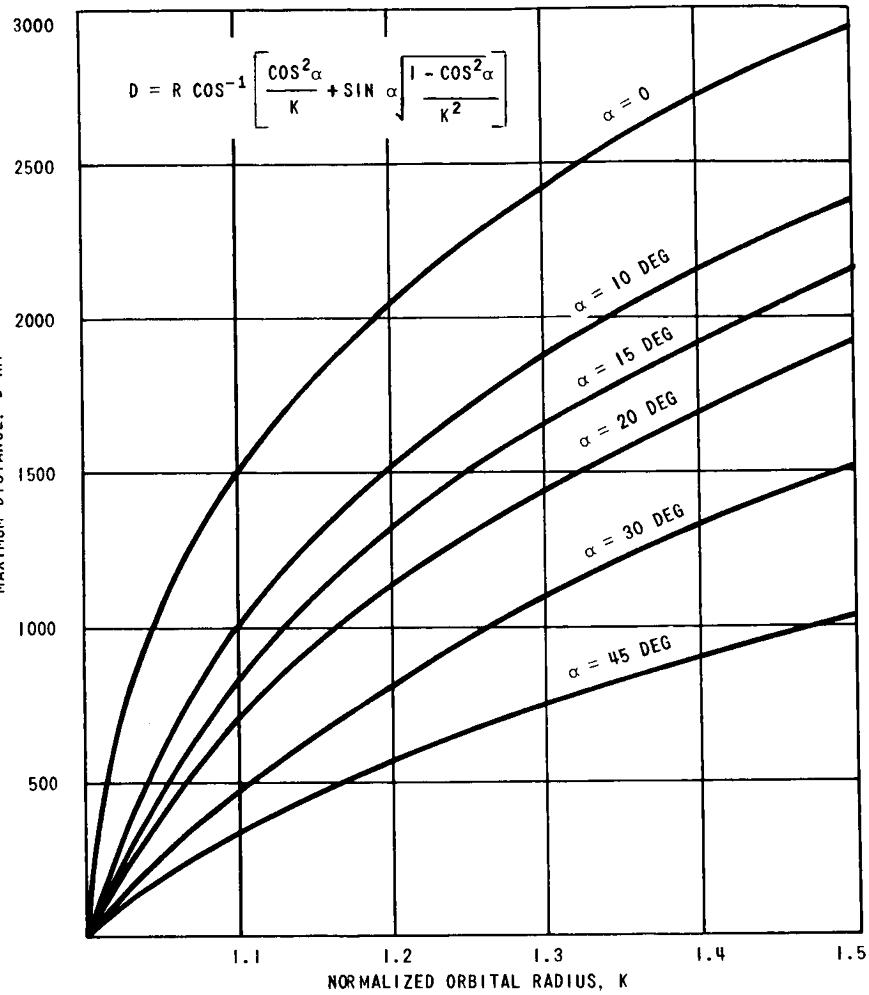

FIGURE 41. MAXIMUM DISTANCE OF SATELLITE VISIBILITY VS NORMALIZED ORBITAL RADIUS (K = 1.0 TO 1.5)

$$D = R \cos^{-1}\left[\frac{\cos^2 \alpha}{K} + \sin \alpha \sqrt{1 - \frac{\cos^2 \alpha}{K^2}}\right]$$

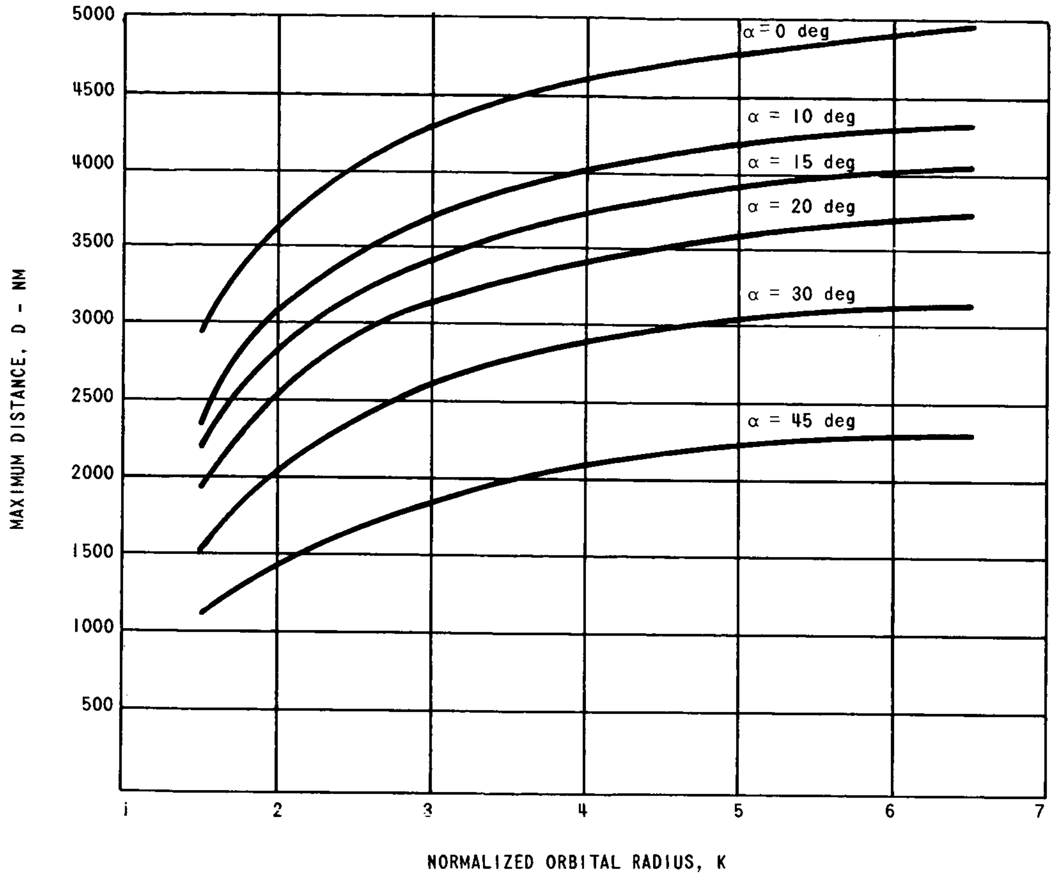

FIGURE 42. MAXIMUM DISTANCE OF SATELLITE VISIBILITY VS NORMALIZED ORBITAL RADIUS (K=1 TO 6) FOR VARIOUS MINIMUM ELEVATION ANGLES

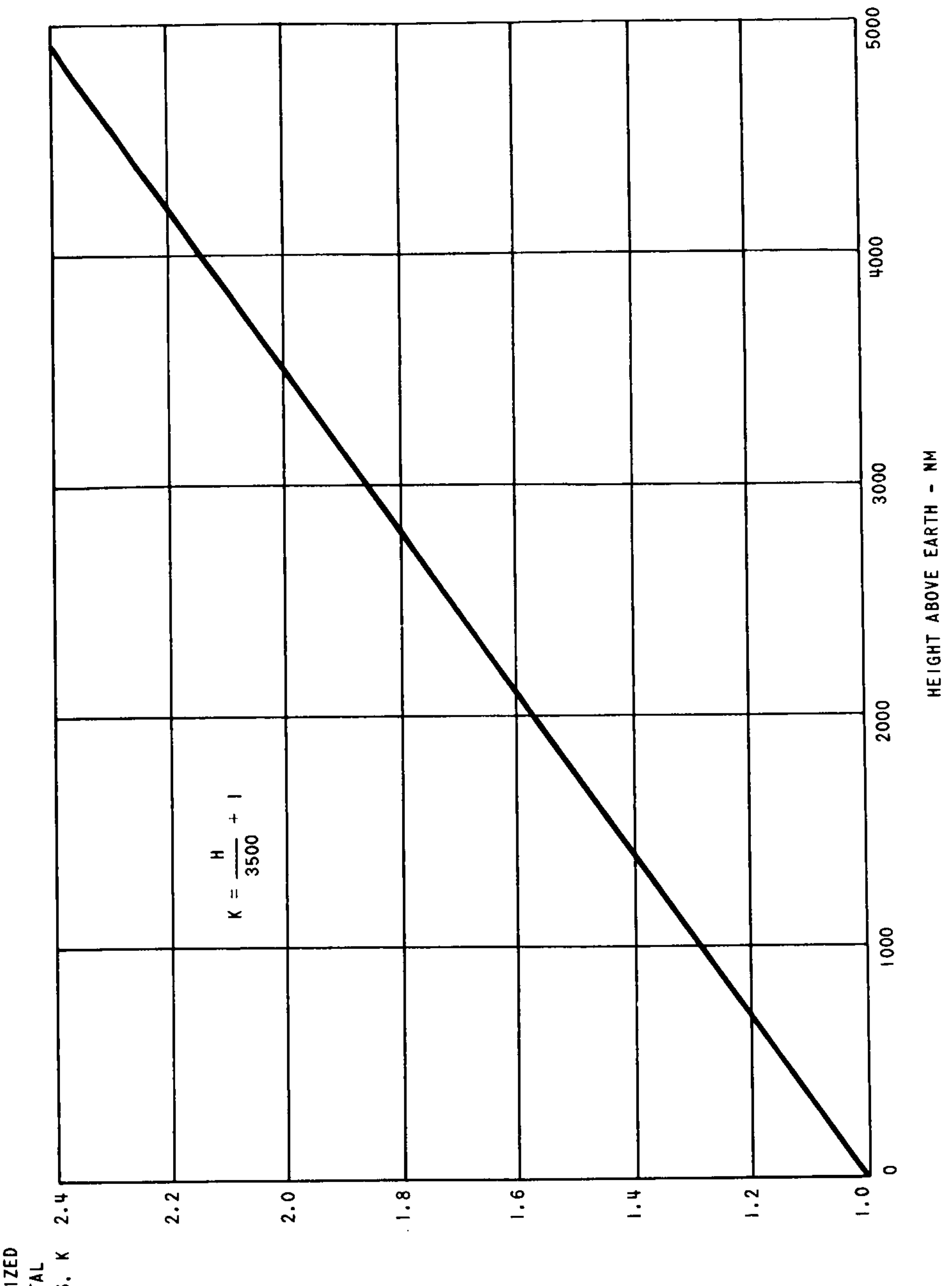

FIGURE 43. NORMALIZED ORBITAL RADIUS VS SATELLITE ALTITUDE

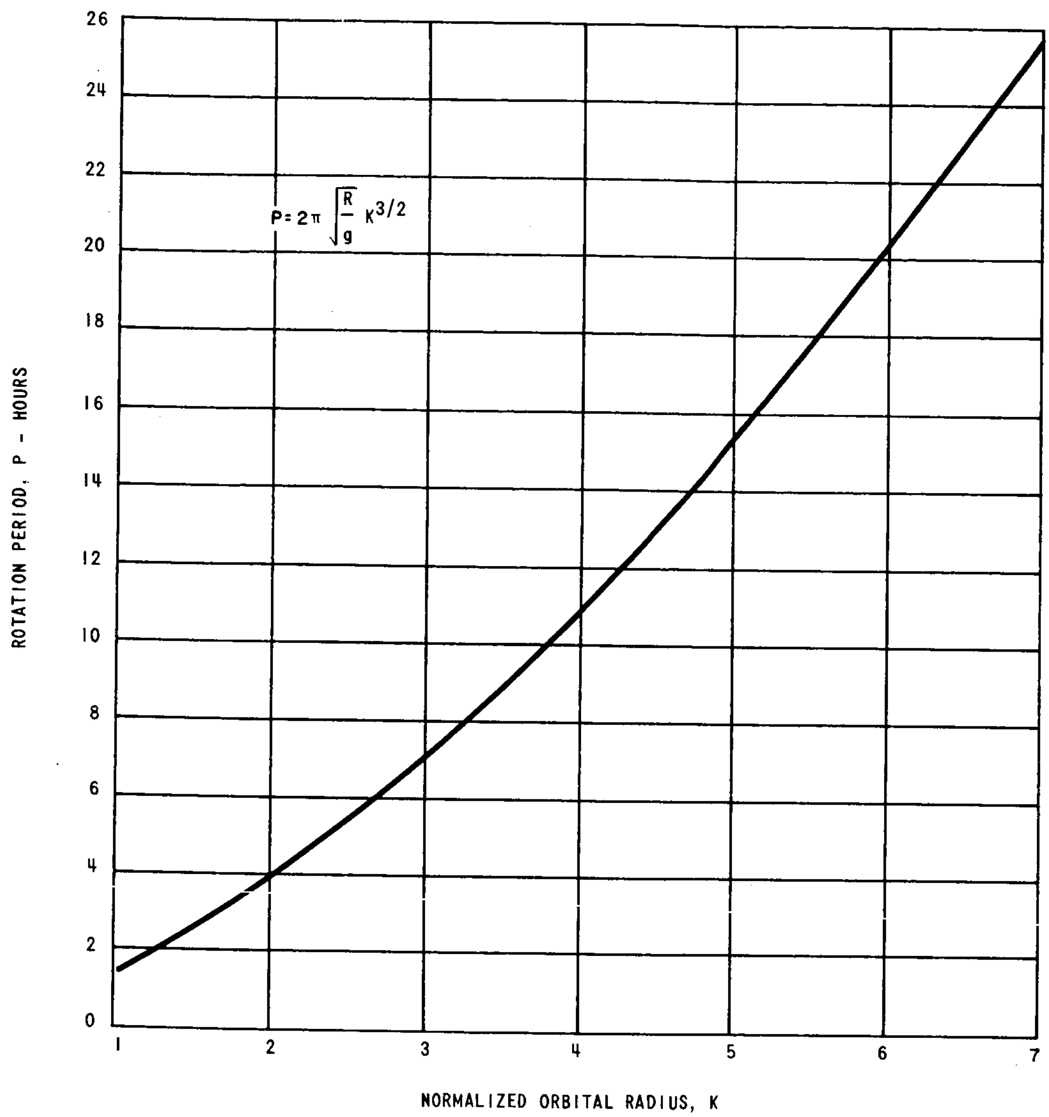

FIGURE 44. SATELLITE ROTATION VS NORMALIZED ORBITAL RADIUS

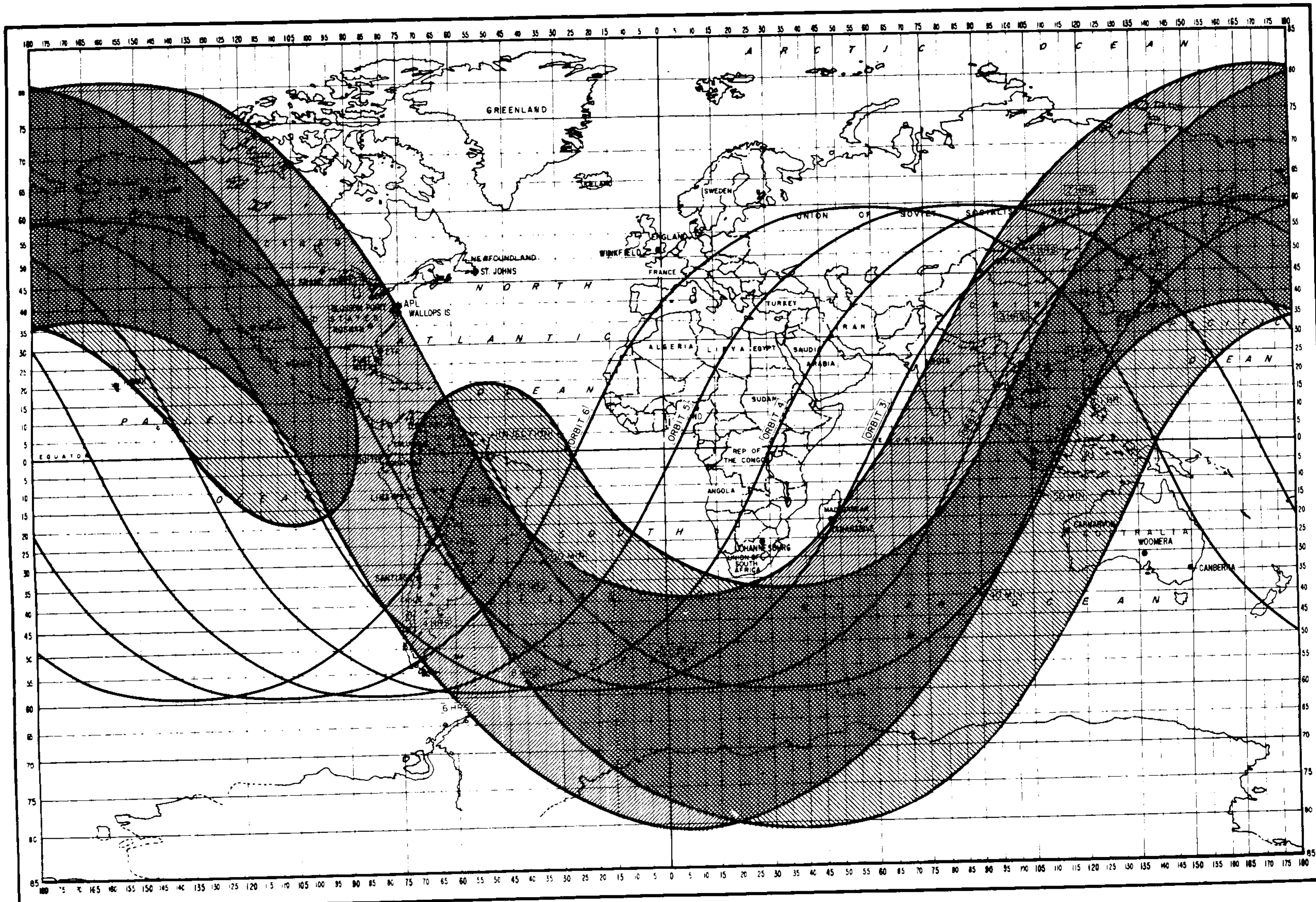

FIGURE 45. COVERAGE OF GEOS-A

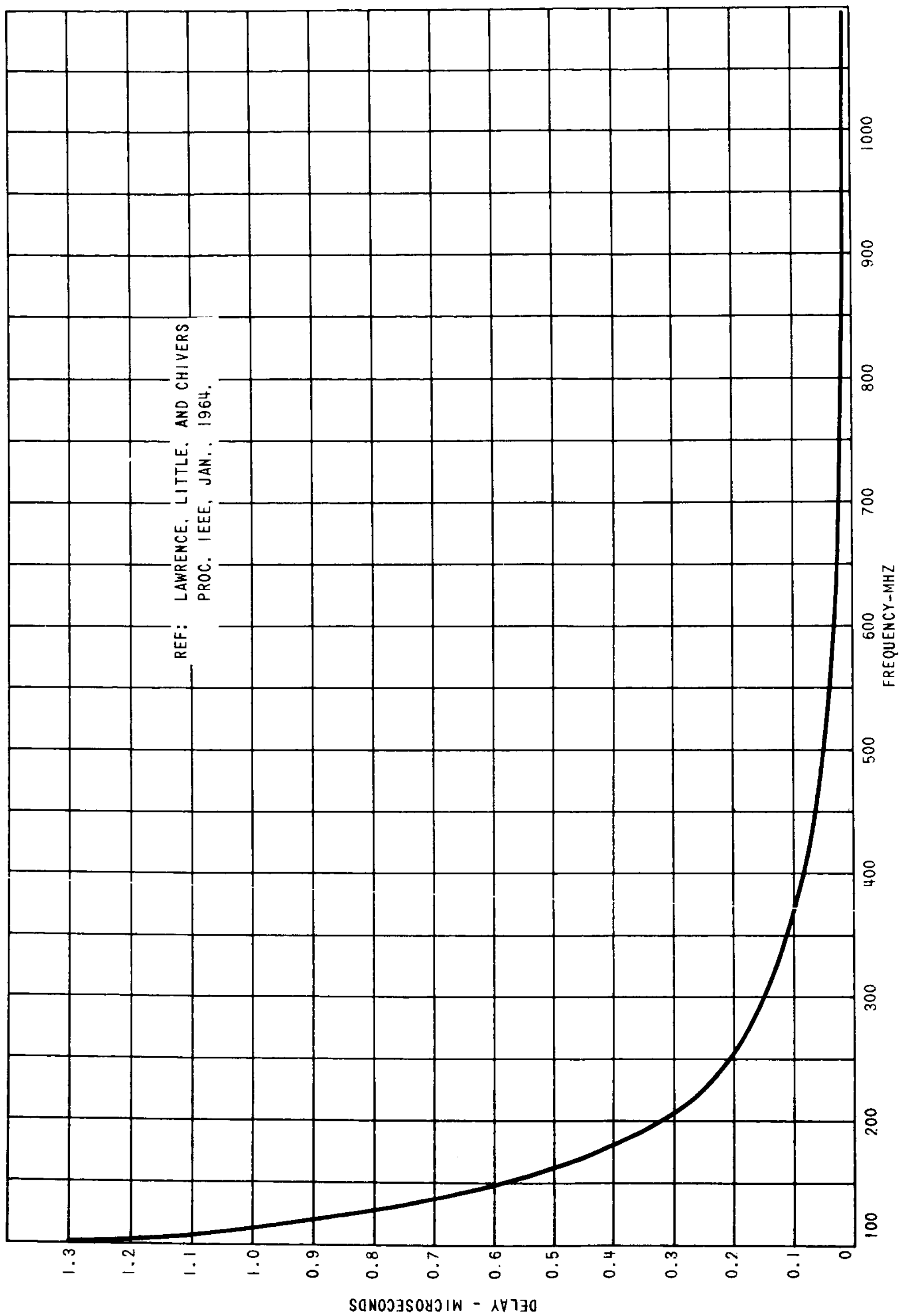

FIGURE 46. IONOSPHERIC RETARDATION OF RADIO WAVES VS FREQUENCY

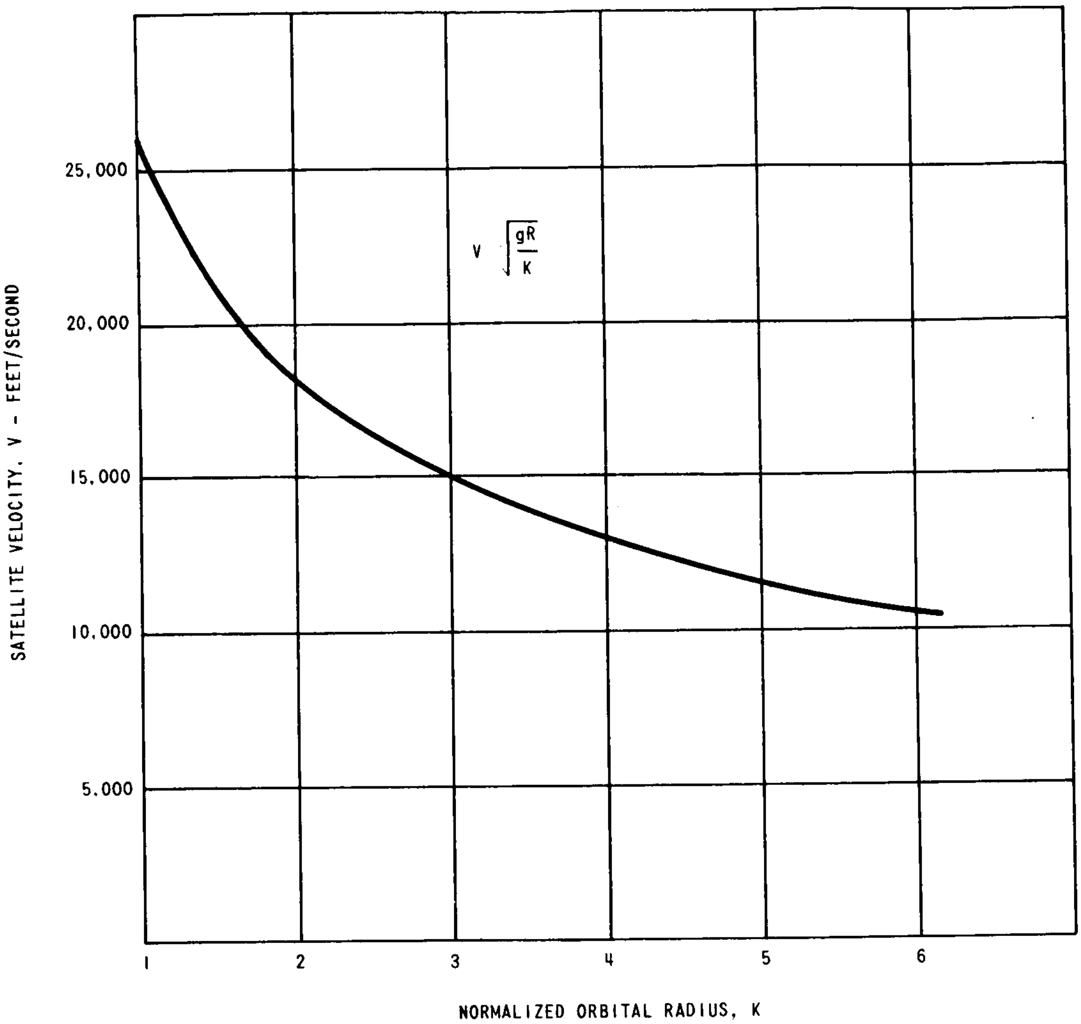

FIGURE 47. SATELLITE VELOCITY VS NORMALIZED ORBITAL RADIUS

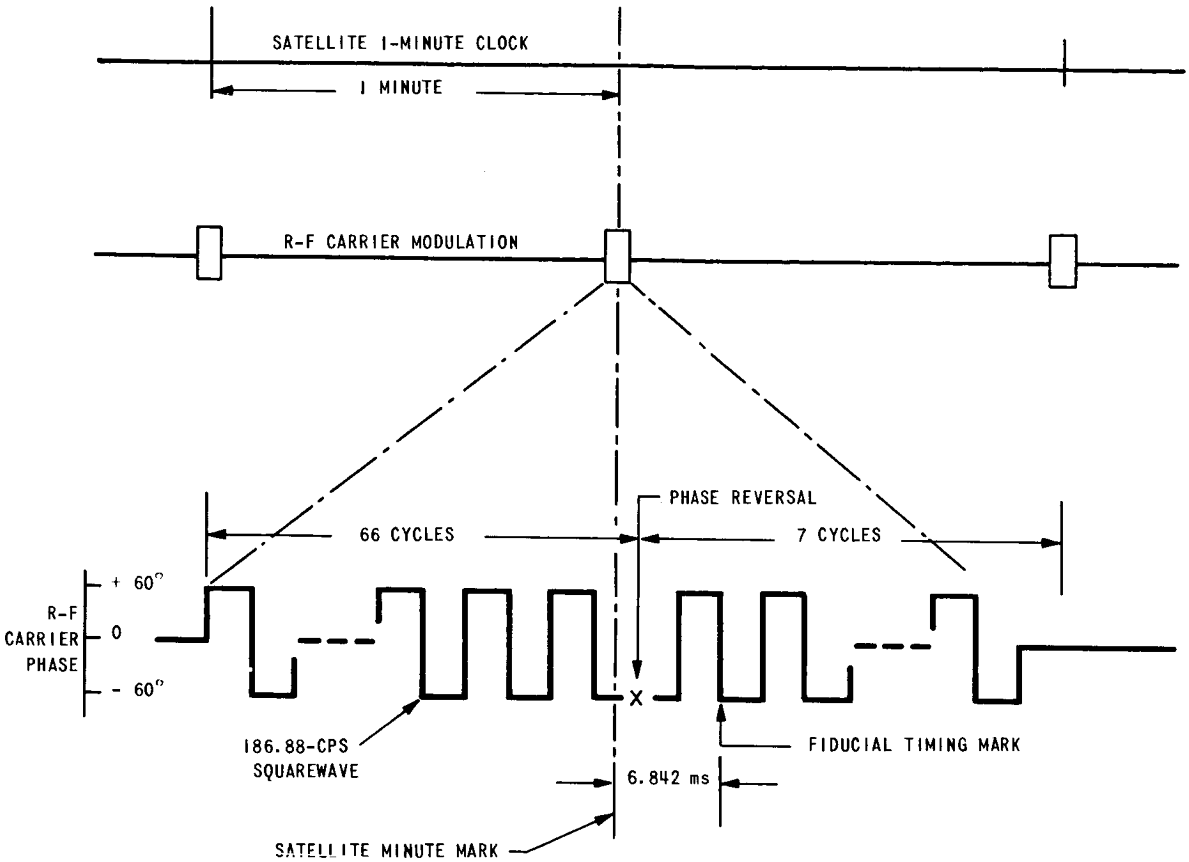

FIGURE 48. GEOS-A TIME MARKER FORMAT

SECTION X

SUMMARY AND CONCLUSIONS

The appreciable length of this report bears testimony that the problem of clock synchronization has already been attacked in a wide variety of ways by many investigators. These ways vary from simple techniques to quite complex ones.

It is also apparent from the findings of this study that for practical use the choice of a clock synchronization system depends upon the requirements of three principal factors:

- Accuracy - the accuracy to which time synchronization is actually required
- Coverage - the area over which the clocks to be synchronized are located
- Accessibility - the difficulty of getting the synchronizing data to the clocks.

The accuracy requirement will affect the cost of the system to a considerable extent; better accuracy will require higher overall costs because of greater system complexity, higher operational costs, and greater logistics of synchronization. No attempt is made here to assign dollar values to these factors since they are, like noise levels, subject to wide fluctuations of an unpredictable nature.

The need for wide area coverage will eliminate many possible systems from consideration. Once again, the cost will generally increase with the separation of the clocks, thus eliminating many candidate systems as the distance increases. The characteristics of each of the systems studied are given in figure 49, which shows the general range of accuracy and distance covered for each.

Accessibility implies not only the ability to carry a Master clock to the Slave clock, but may also include the availability of certain radio signals. For example, a submerged submarine can receive VLF signals but no others.

While no recommendation for a specific clock synchronization system can be made since no requirements have been established, it is felt important at this time to make this one point: Do not overlook the possibilities of obtaining both accuracy and low cost in the combination of a clock stabilized by reference to VLF signals and set once by a Master clock.

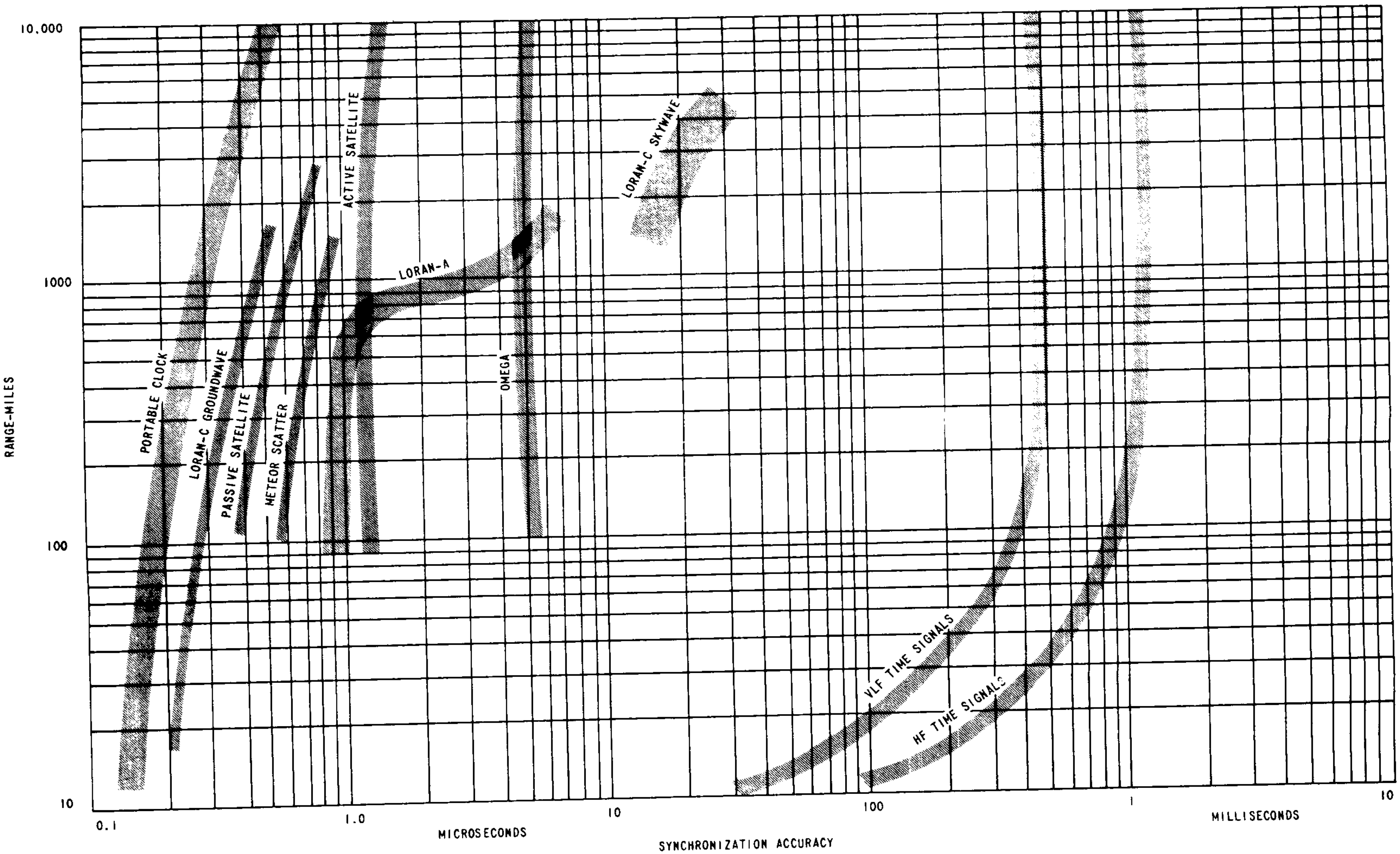

FIGURE 49. ACCURACY AND RANGE OF VARIOUS CLOCK SYNCHRONIZATION TECHNIQUES

SECTION XI

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APPENDIX I

ELEMENTS OF TIME SYNCHRONIZATION

A. INTRODUCTION

This appendix first discusses the fundamental considerations related to uniform time scales and their functions. Having established this background for the elements of time synchronization in detail, the appendix continues with an analysis of synchronization control systems - both discontinuous and continuous - and their characteristics.

The time-scale discussion includes coverage of phase, ambiguity, mathematical representation of the functions, frequency, relative phase, timing errors, timing accuracy and relative phase, and synchronization.

In discussing the characteristics of continuous synchronization control systems, the considerations that must be given to types of correlation functions, general system control functions, synchronization error functions, and to continuous linear control systems are presented.

For the purposes of this study, time is assumed to be an essentially intangible quantity that can only be observed through the evolutions of some physical entity - itself a function of time - such as the rotation of a shaft, the distance between objects moving with different velocities, the decay of the intensity of radioactivity, or the successive vibrations of a physical oscillatory system.

B. FUNDAMENTAL CONSIDERATIONS OF TIME SCALE FUNCTIONS

Uniform time scales are established by reference to theoretically "invariant" physical laws; e.g., the laws of motion, or the laws of radioactive decay, etc.

For example, according to Newton's First Law when two masses rotate about a common axis with different angular velocities in the absence of external torques, the angular difference between the masses increases linearly with time and, hence, delineates a theoretically-exact time scale.

Similarly, the activity of an undisturbed volume of radioactive material varies logarithmically with time. Thus, the passage of the level of radioactivity through successive orders of magnitude (with respect to any convenient base) provides a succession of identifiable epochs,[7] evenly spaced in time, from which the times of occurrence of other events of interest can be determined.

To be useful, a time scale must be predictable; i.e., the successive epochs of the scale must delineate known increments of time which, for most purposes, should be equal in length. Moreover, the physical parameter delineating the time scale should provide a succession of uniquely detectable epochs to which the times of occurrence of other events of interest can be precisely related.

While a continuous non-periodic time-scale function, such as radioactive decay, would be convenient (since it would be without ambiguity), such a scale is for most purposes impractical because of poor resolution. For example, a time scale readable to 1 second, and spanning only the period of a man's lifetime, would have to possess a resolution of at least $1{:}10^9$.

Thus, with few exceptions (e.g., radioactive carbon dating) all time-scale functions are periodic functions of some kind - such as the rotation of a shaft or dial, planetary motion, the swing of a pendulum, atomic vibration, electric oscillation, etc. - combined with a means for counting or otherwise keeping track of the total number of periods that have occurred since some arbitrary "time zero." By this means the resolution ratio can be expanded almost indefinitely since it is bounded only by the ability to maintain the total count without error.

Classically, the reference time-scale - to which all measurements of time were ultimately referred - used to be the rotation of the earth about its axis. Then when timing measurements were refined to the point where the perturbations of the diurnal period became intolerable, the Mean Solar Year was adopted as the standard time scale, with the zero epoch of the scale being the instant of commencement of the Year 1900 AD. In turn this time scale has now been displaced - at least tentatively - by Atomic Time, a scale based upon the aggregate of the electronic oscillations arising from energy transitions of a very large number of cesium or hydrogen atoms.

1. Phase

Inherent in the concept of time scale functions, particularly that of periodic functions, is the concept of phase (i.e., the subdivision of each period of the time scale into distinguishable parts) whereby the time of occurrence of an event can be characterized by the particular subdivision or phase of the period in which it occurs; as for example, dividing the day into morning, afternoon, and night and characterizing an event as having occurred in the "forenoon."

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[7] The word "epoch" is defined by Webster's New International Dictionary as "A point of time, determined by some significant event, with reference to which dates are reckoned."

For obtaining increased resolution and linearity of scale it is convenient to divide the basic period into a much larger number of more or less uniform phases; i.e., the time scale is considered to be a function of an auxiliary variable or "argument" depicting successive phases in each scale period. Thus a day is divided into 24 hours, 1440 minutes, or 86,400 seconds. The second is divided into a million microseconds and the microseconds separated into a thousand nanoseconds. Thus the time of occurrence of an event can be characterized by its having occurred (or at least started or finished) during a particular hour, minute, second, or microsecond - as appropriate. Under alternate conditions where the time scale is a rotating shaft or dial, or is a sinusoidal function such as an alternating current or voltage, the "argument" of the time scale would be a rotation - with increments or phases expressed in degrees, radians, or mils, etc., and the timing of an event characterized by the particular increment of rotation in which it occurs.

Generically, the term phase refers to a subdivision of a time period; in the evolution of a time scale, successive phases succeed one another in an unending temporal stream.

Where the duration of a phase is large compared with some event, the entire event may be said to have occurred during the particular phase of the scale. With finer subdivisions, only a particular epoch of an event - such as the beginning or the end, or a null point or zero crossing - may be encompassed by a particular phase of the time scale; and in the limit, as the duration of each phase element tends to zero and the number of phases increases without limit, each phase element comes to define a particular instant of time.

The term phase has also come to mean the same as "phase difference": i.e., the number of phase units by which an event in time leads or lags another, particularly when one epoch is a reference time base to which the timing of other events is referred. Thus, a sinusoidal function going through its maxima one-eighth cycle before those of a similar reference function has a phase of plus 45 degrees, or $\pi/4$ radians.

Similar time-scale functions, if aligned in time, necessarily evolve in unison through successive elements of phase; it therefore follows that if one time scale is displaced a given number of phase units with respect to another of the same period, that same "phase difference" must exist between every corresponding pair of phase elements of the two scales.

Thus - although the successive phase elements of a particular time scale follow one after another in an unending temporal stream - the "phase difference" representing the displacement of one time scale with respect to another of the same period is a constant stationary quantity, independent of time as long as the relative displacements of the two scales remain unchanged.

In defining the phase of a time scale, the reference to which it is related does not have to be a function of the same shape or form. It need only supply timing epochs of the same period. If the reference function is of the same shape, the same phase difference must necessarily exist between every pair of similar points of the two functions. If the functions are not similar in shape, the points between which the phase is measured must be specified. Thus, for example, the positive maxima of a sinusoidal function may be leading a series of timing pulses of the same period by 45 degrees. Concurrently, the positive-going zeros of the sinusoid will be lagging by the same amount and the negative maxima will be lagging by 135 degrees.

With discontinuous functions such as pulse trains, squarewaves, and discontinuous sawtooth waves, etc., the phase can only be established between distinguishable epochs of the waves and is undefined elsewhere. With such functions, however, if the two waves have the same period, the phase difference between given epochs in each period will always be the same; and this difference is considered to be a constant independent of time rather than a periodic function recurring with the same value.

2. Ambiguity

Where the epoch of an event in some scale of time is characterized by the phase at which it occurs within a scale period, the indication is ambiguous since a similar phase recurs in every period of the scale. Thus it is necessary to identify the particular period, as well as the phase of the epoch, to identify uniquely its time of occurrence.

The identity of the period may be established in several of the following ways:

- By totaling the periods elapsed since some arbitrary "time zero," with some counting means that assigns a unique count to each period
- By providing a graduated set of auxiliary time scales of longer periods and lower resolution, so related that an element of phase of any one scale is equivalent to - and hence identifies - a whole period of the next shorter period scale
- Combinations of the foregoing two methods.

Totaling the number of periods elapsed since an arbitrary time zero is the mechanism used in all electronic-crystal and atomic clocks - as well as in wrist and pocket watches, pendulum clocks, etc.

All practical counting mechanisms (except, perhaps, the aggregate memory of a large human population passing the total count of the years to succeeding generations) have an upper limit of one kind or another, beyond which the count either repeats or fails. Hence, such time-scale functions are still periodic and ambiguous; but the period can be extended to the point of no significance without compromising resolution simply by increasing the maximum count available to the mechanism.

Also, since a finite probability of a miscount always exists, the final count has at all times some element of uncertainty that increases with the square root of the total and which cannot be resolved except by reference to some other scale of time.

Totaling the number of periods is the basic method of period identification utilized in watches and clocks, since the escapement mechanism and its gearing to the clock hands is in itself a mechanism for totaling oscillations of the balance wheel or pendulum.

However, the dial itself (and its gearing) constitutes a mechanism for combining the phase of long period scales to resolve the ambiguity of scales of shorter period, thereby extending the ratio of period-to-resolution. Thus, the second hand can be read to 1-second increments, and repeats over a 60-second period. If correctly aligned, the minute hand can be read to an accuracy of perhaps 10 to 20 seconds and can therefore easily identify 1 revolution of the second hand, thus extending the unambiguous range to 60 minutes. The hour hand (again, if properly aligned) can be read to within approximately one-quarter hour and therefore labels each revolution of the minute hand over a period of 12 hours.

Beyond this, unless the instrument is fitted with a day-of-the-month dial, the count must usually be extended by biologic memory or some other external means such as simply knowing whether it is morning or afternoon, and knowing the day of the month or week.

It should be pointed out that a calendar is not a time keeper; it is simply a static memory aid that gives the noncommensurate relations between the day of the month and the day of the week. The timekeeper is the mind of the observer, holding a mental count of the succession of days.

3. Mathematical Representation of Time Scale Functions

All practical time-scale functions are oscillators; e.g., a pendulum or balance wheel in a clock, an electrical oscillator, or a molecular or atomic resonance, etc. Since the physical environment always has some random element, the successive periods of any physical oscillation differ by some small random amount. Pivot friction, buffeting by gas molecules, random slippage of the molecular lattice in restoring springs, etc., are involved in mechanical oscillations; while random thermal agitation occurs in electric oscillations. In nuclear or molecular resonances the resonance effect is itself provided by the aggregate of a very large number of atoms or molecules whose individual changes in energy state occur randomly.

In addition to random variations, there may also be systematic changes such as mechanical relaxations, "aging" effects, evaporation of mass, permanent realignment of crystalline structures, or changes in gas pressures - all of which cause a systematic drift in the duration of successive periods.

Hence, the periods of any physical oscillator vary one from another by some random account (σ) which may be infinitesimal, but over the summation of millions or billions of oscillations the variation is not insignificant and may produce a gradual systematic increase or decrease in the lengths of the successive periods.

Thus, time scale functions are not periodic functions of time, but of an auxiliary variable or "phase" that is itself a more or less smooth function of time.

Mathematically, such a function might be represented by the expression

$$S(\varphi) = S(\varphi \pm 2\pi N)$$

where $S(\varphi)$ defines the shape of the periodic function over any period, 2π, and the function repeats its shape over successive periods of the argument, φ.

Argument φ may then be a more or less smooth linear function of time, perhaps given by

$$\varphi(t) = \varphi(0) + \int_0^t \omega(t)dt + \theta(t)$$

where $\varphi(0)$ is the initial phase or setting error at time zero, $\omega(t)$ is the smooth rate of change of phase, and $\theta(t)$ is a random phase increment representing random fluctuations in the lengths of the successive periods of the argument.

Such time scale functions can be represented by a complex exponential function of the argument taking the form of

$$S(\varphi(t)) = \sum_p^q C_n \, e^{jn\varphi(t)}$$

where

$$C_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} S(\varphi) \, e^{-jn\varphi} d\varphi$$

defines a set of coefficients giving the shape of $S(\varphi)$ over each period of 2π radians.

a. Exponential Decay

If, for example, the time scale is a radioactive decay,

$$p = q = 1$$

and

$$\varphi(t) = ja(t/T)$$

$$S(\varphi(t)) = C_1 \, e^{-a(t/T)}$$

with successive epochs of the scale, where "t" is equivalent to nT, being defined by the amplitude of $S(\varphi(t))$ passing through successive orders of magnitude given by

$$S(jaN) = e^{-aN}$$

b. Shaft or Dial Rotation

If the time scale function is the rotation of a shaft or dial, its angular position may be represented by the phase, $\varphi(t)$, of a complex phasor in accordance with the expression

$$S(\varphi(t)) = e^{j\varphi(t)} = \cos \varphi(t) + j \sin \varphi(t).$$

c. Sinusoidal Function

If the time scale is a sinusoidal function (such as an electric or other oscillation), it would be represented either by the real part of a rotating complex phasor, as in the previous equation, or by half the sum of the phasor and its conjugate as in the following equation in which

$$S(\varphi(t)) = (1/2)\left(e^{j\varphi(t)} + e^{-j\varphi(t)}\right)$$

$$S(\varphi(t) = \cos \varphi(t)$$

d. Pulse Functions

If the time scale function is a pulse or other nonsinusoidal periodic function, it would be represented formally by

$$S(\varphi(t)) = \sum_{-\infty}^{+\infty} C_n e^{jn\varphi(t)}$$

where the set of C's defines the shape of the scale function, and $\varphi(0)$ and $\theta(t)$ give the offset and variation from a smooth linear function of time.

4. Frequency

The number of periods through which the time scale evolves per unit of time is the "frequency" of the time scale. By definition a time scale, $S(\varphi)$, is exactly periodic in the auxiliary phase variable, φ; i.e., $S(\varphi \pm 2\pi N)$ equals $S(\varphi)$ for any value of φ and all integral values of N. However, phase $\varphi(t)$ is not necessarily a strictly linear function of time, t, so that the time duration of the successive periods of $S(\varphi)$ varies with time - as given by inversion of the relationship

$$\varphi(t + T) - \varphi(t) = 2\pi$$

Expanding in series, and recognizing that t is much greater than T, this relationship can be expressed as

$$(\omega(t) + \dot{\theta}(t))\ T = 2\pi$$

from which

$$F = \frac{1}{T} = \frac{\omega(t)}{2\pi} + \frac{\dot{\theta}(t)}{2\pi}$$

where the first term on the right is the smooth rate of change of phase and the second term is a random variable representing the random fluctuations in the number of periods per unit of time.

5. Relative Phase

The relative phase between two time scales can be expressed as

$$\varphi_{1,2} = \theta_1(0) + \omega_1 t + \theta_1(t)$$
$$-(\varphi_2(0) + \omega_2 t + \theta_2(t))$$

If the scale periods are equal,

$$\omega_1 = \omega_2 = 2\pi/T$$

and the phase difference reduces to

$$\varphi_{1,2} = \varphi_1(0) - \varphi_2(0) + \theta_1(t) - \theta_2(t)$$

Time scale functions have existence only at the present instant; the past is gone and the future has not yet occurred. Hence, the phase difference between time scales likewise exists only in the present, although the times of occurrence of events of interest with respect to some scale can of course be recorded and stored.

In general, the arguments of time scale functions can be shifted with respect to one another so that the relative phase can have different values in successive increments of time. If the phase difference changes uniformly with time, the relative phase of two time-scale arguments can be written as

$$\varphi(t) = \varphi_o + \dot{\varphi}(t)$$

where $\dot{\varphi}$ is the rate at which the relative phase is changing.

Now, the relative phase has been given as

$$\varphi(t) = \varphi_1(t) + \omega_1(t) - (\varphi_2(0) + \omega_2 t)$$

Equating these two expressions for $\varphi(t)$ then gives

$$\varphi_1(0) - \varphi_2(0) + \omega_1 t - \omega_2 t = \varphi_o(0) + \dot{\varphi} t$$

If this expression is to be true for all values of time, then

$$\varphi_1(0) - \varphi_2(0) = \varphi_o(0)$$

$$\omega_1 - \omega_2 = \dot{\varphi} = 2\pi\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

Thus, a rate of change of phase is equivalent to a frequency difference or difference in the periods of the two time-scale functions.

6. Timing Errors

The "timing error" is defined as the departure of the phase of a time scale function from the theoretically ideal time scale it represents.

A theoretically exact time scale would have a radian argument or phase of the form

$$\varphi_o(t) = \varphi_o(0) + (2\pi/T_o)t = \varphi_o(0) + \omega t$$

where $\varphi_o(0)$ is the assigned phase of the scale at time-zero (which may, but need not necessarily, be zero), T_o is the duration of each scale period, and ω (which equals $2\pi/T_o$) is the rate of change-of-phase or "radian frequency."

Any physically realizable time scale will have an argument of the form

$$\varphi_{(t)} = \varphi(0) + \int_0^t [\omega(t)\, dt + \dot{\theta}(t)]\, dt$$

where $\varphi(0)$ again is the phase at time zero, $\omega(t)$ is the smooth timing rate or frequency (of the time periods), and $\theta(t)$ is a random variable giving the fluctuations of the phase with respect to the constant rate.

The difference between this function and the theoretically uniform time scale it represents is given by

$$E(t) = \varphi(0) - \varphi_0(0) + (\omega - \omega_0)t + \theta(t)$$

where $\varphi(0) - \varphi_0(0)$ is the scale offset or "setting error," $(\omega - \omega_0)$ is the mean rate error, and $\theta(t)$ again represents the random variations with respect to the smooth linear function of time.

The "mean" rate error $(\omega - \omega_0)$ depends upon how accurately the time scale frequency matches the ideal frequency and also upon how it "ages." The presence of this offset in frequency produces a timing error that increases at least linearly with frequency and perhaps at an even higher order, unless by chance or design the various terms of the aging function tend to cancel over the useful life of the time scale.

The total random error at any time (t) is the linear sum of the variations in the lengths of the included periods. Assuming the statistical distribution of the individual fluctuations to be gaussian, the root-mean-square error at any time (t) after an initial setting would be the rms value of the fluctuations of the periods multiplied by the square root of the number of periods. This relationship can be expressed as

$$\sigma\sqrt{t/T} = \sigma\sqrt{N}$$

Hence, the root-mean-square error of the time indication also varies as the square root of the time elapsed since the time scale was initially set.

From this reasoning it follows that no matter how accurately the rate and initial settings of a time scale are established, its deviation from the ideal uniform time scale it represents can be expected to increase as the sum of a linear or higher order systematic drift - in addition to a random walk with an rms value that increases with the square root of time.

Thus, independent time scales - no matter how well constructed or how carefully adjusted - are never synchronous over all time, although the error can be held to less than some particular value over some interval.

Since time itself is intangible - being observable only by the evolution of some physical function of time, which is always subject to setting errors, rate errors, and random fluctuations - it is impossible to have a theoretically exact time-scale function and the absolute error with respect to theoretical time cannot be determined.

A theoretically uniform time-scale of known period can be approached as closely as desired, however, by the consensus of a very large number of independent primary time scales. For this condition the mean time scale would have an argument given by the expression

$$\varphi_m(t) = \bar{\varphi}(0) + \bar{\omega}(t) + \bar{\theta}(t)$$

in which case, the offset and variations would be reduced statistically by the square root of the number of independent functions included in the consensus.

7. Relation of Frequency Uncertainty to Timing Accuracy

Frequency was defined as the number of periods of the time scale per unit of time. Thus, assuming that the argument, $\varphi(t)$, of the time scale is in radians and a period of the time scale function corresponds to 2π radians, the following relationship exists.

$$\text{frequency} = f = \frac{1}{2\pi}\ \frac{\varphi(t_2) - \varphi(t_1)}{(t_2 - t_1)}$$

Substituting the foregoing expression for $\varphi(t)$; viz.,

$$\varphi(t) = \varphi(0) + \omega t + \theta(t)$$

where $\varphi(0)$ is the initial or setting error, ω is the smooth rate of change of phase or frequency, and $\theta(t)$ is the random fluctuation component,

$$\text{frequency} = f = \frac{1}{2\pi}\ \frac{\varphi(0) + \omega t_2 + \theta(t_2) - \varphi(0) - \omega t_1 - \theta(t_1)}{(t_2 - t_1)}$$

where t_1 and t_2 are the beginning and end, respectively, of the interval over which the frequency is determined.

This reduces to

$$f = \frac{1}{2\pi}\left(\omega + \frac{\theta(t_2) - \theta(t_1)}{t_2 - t_1}\right)$$

which, within the limit as $t_2 - t_1$ approaches zero, becomes

$$\text{frequency} = f = \frac{1}{2\pi}(\omega + \dot{\theta}(t))$$

That is, the instantaneous frequency is equal to the smooth rate of change of phase plus the rate of change of the random fluctuations.

The variance between elements of an ensemble of R different determinations of frequency is given formally by the expression

$$V_f = \frac{1}{R}\sum_R (f_r - \bar{f})^2$$

If the fluctuations of the period lengths are gaussian, the ensemble averages of the fluctuations are zero so that $\bar{f}$ is simply $\omega/2\pi$ and the expression for variance then becomes

$$V_f = \frac{1}{4\pi R^2} \sum_R \frac{\theta_r(t_2) - \theta_r(t_1)}{t_2 - t_1}$$

Now, $\theta_r(t_2) - \theta_r(t_1)$ is simply the sum of the fluctuations accumulating between t_1 and t_2 in the r^{th} determination of frequency and is given by

$$\theta_r(t_2) - \theta_r(t_1) = \sum_N e_{rn}$$

and the interval $t_2 - t_1$ is NT where T is the mean length of a period. Hence, the variance, V_f, over the ensemble of R determinations of the frequency becomes

$$V_f = \frac{1}{4\pi R^2} \sum_R \left[\frac{1}{NT} \sum_N e\right]^2$$

Again, if the distribution of the fluctuations of the period lengths is gaussian, the square of the sum of the fluctuation is equal to the sum of their squares and 1/N times the sum of the squares is the mean square value, σ^2; hence

$$V_f = \frac{1}{4\pi R^2} \sum_R \frac{\sigma^2}{NT^2}$$

which immediately reduces to the rms fluctuation in frequency as

$$\sigma_f = \frac{1}{2\pi\sqrt{N}} (\sigma/T)$$

Thus, the apparent fluctuation in frequency varies inversely as the square root of the number of periods or length of observation - in contrast to the fluctuation in phase, which varies directly with the square root of these quantities.

8. Synchronism

In its most elementary form "synchronism" implies the existence of similar time scales evolving through successive phases and periods at exactly the same rates - as, for example, clocks ticking in unison.

The concept of synchronism also includes time scales of commensurate as well as identical periods - as, for example, two pulse trains in which every p^{th} pulse of one has a fixed phase with respect to the q^{th} pulse of the other. Under these conditions pulses with the given phase difference then recur at the least common multiple period, T_m, according to the equation

$$T_m = T_a/q = T_b/p$$

Then by eliminating all other pulses the original sequences are transformed into sequences with the common multiple period and a constant phase difference which renders them synchronous.

Similarly, if each period of the first sequence is divided into q phases and each of the second into p phases, the pulse trains would again be transformed into sequences of equal period and fixed phase with a period that is now the greatest common divisor. This relationship is expressed by

$$T_d = T_m/pq$$

The foregoing concept of synchronism must be broadened to include the case of two commensurate time scales whose common-divisor phase difference is variable but bounded; i.e., the phase difference never exceeds some maximum absolute value - as, for example, a synchronous motor which must run synchronously with the line voltage but always lags by a small power angle, varying with the load.

Thus, for the purposes of this study, synchronism will imply that the periods of the time scale functions involved are at least related by rational numbers; i.e., these periods possess a rational common multiple and a rational common divisor, however far removed, and the phase difference between related time scales based upon the common divisor period is at least bounded.

9. Ambiguity of Time Scales of Unequal Period

Where the phase of a time scale is determined with respect to a reference scale of different though commensurate period, the period of the ambiguity is that of the greatest common divisor rather than that of the time scale itself. This situation is depicted in figure 50, which shows the relative phase of a time scale with three quarters of the period of a reference scale progressively shifting to the right on succeeding lines of the diagram.

By definition, the relative phase of this time scale is the least number of phase units from any epoch of the reference to the next following epoch of the scale.

On line zero, every fourth epoch of the scale coincides with every third epoch of the reference. These reference epochs are identified by the symbol A and intermediate epochs of the reference are identified by B and C, respectively.

As the time scale is shifted with respect to the reference, the phase lags progressively until the shift amounts to a whole period of the greatest common divisor; whereupon adjacent epochs of the scale coincide with the B-epochs of the reference, which, according to the definition, now define the relative phase.

A further shift of another period of the greatest common divisor (one-quarter of the reference scale period) brings epochs of the scale into coincidence with the C-epochs of the reference, thereby causing the phase cycle to repeat again.

Thus if there is no means for identifying one period of the reference from another and if the phase of the time scale is taken to be the minimum phase in any three successive periods of the reference, the phase repeats over a quarter period of the reference; i.e., over a period of the greatest common divisor.

10. Time Synchronization

Since all time-scale functions are subject to random walk as well as to at least some uncertainty in the adjustment - however infinitesimal - of their mean timing rates, the relative phase of two independent time scales is always unbounded and ultimately tends to infinity. Hence if two or more time scales are to remain in phase, some external control must be applied to keep them in synchronism.

Where one time base is constrained to maintain synchronism with respect to another, the relative timing error is then bounded and the timing error statistics are stationary; however, perfect synchronization is unattainable and there will always be small error - both random and systematic, and also random in time.

Time synchronization is the process of changing the phase and/or rate of change-of-phase of a time scale function as may be required to restrict its deviations with respect to some other time scale to less than some particular amount. An example of this process would be the adjustment of the regulator and resetting the hands of a clock from time to time so that its deviation with respect to a radio time signal is kept below some maximum value.

Synchronization is always accomplished by adjusting the phase and/or timing rate or frequency of the controlled time scale in accordance with its phase difference with the standard to which it is being synchronized. Mathematically, such an operation is described by the expression

$$\varphi(t) = F\,(\varphi_1(t) - \varphi(t)$$

where $\varphi_1(t)$ is the phase of the time standard (plus any noise or other disturbance with which it may be contaminated) with respect to some absolute time reference, $\varphi(t)$ is the phase of the local time scale with respect to the same reference, and F represents whatever control procedure is applied.

Thus time synchronization is essentially a feedback control operation, and all of the vast literature concerned with the characteristics and applications of such systems is applicable.

Particularly from a "black box" point of view, a time scale synchronizer can be considered to be a transducer operating on the timing standard (plus noise, interference, drift, and any other disturbances which may be present) to produce the local time scale. Such a synchronizer will have a transfer characteristic adapted to minimize deviation from the standard and minimize random fluctuations in the face of the aforementioned noise and other disturbances.

Many different types of feedback control can be and are used for time synchronization, depending upon the requirements of the application. These controls vary from simply manual resetting from time to time, as required to keep the maximum offset below some acceptable limit, to highly sophisticated automatic control systems. Such systems, which act not only in response to the immediate phase displacement but also to the rate of change of phase and/or the integral of the phase error, etc., may introduce an open-end correction for an assumed aging function of the time scale generator.

All such systems, however, reduce to the following three basic components:

- The source of the time scale function being synchronized
- Means for detecting the phase deviation of the controlled time scale with respect to some standard
- A controller adjusting the timing rate and/or the phase of the time scale function being synchronized in response to the observed differences.

Such control systems are always more or less discontinuous, ranging from completely discontinuous control to substantially continuous control systems. In the former device, the phase difference is sampled and the timing corrected only at substantial intervals, with the inherent stability of the time scale being depended upon to maintain phase within the desired limits in the interim. In the latter control system, sampling is so frequent that no significant phase drift can occur between samples.

The adjustments may be accomplished by actually resetting the phase and rate of the basic time-scale oscillator, or by offsetting the totaling mechanism keeping count of the periods (as when resetting the hands of a clock or watch). The adjustment could also be simply a record of measurements of offset and rate that could be applied to predict the phase with respect to some scale of standard time at any time thereafter - as is done with a ship's chronometer - or it could be a combination of the foregoing methods.

The adjustment may be a more or less fixed amount applied from time to time, as required, whenever the timing error exceeds some acceptable value; or the adjustment may be an amount, depending upon the error, that is applied at more or less regular intervals.

In the limit where the time between successive phase or rate corrections becomes negligibly small, the synchronization control is continuous. However, no physical control system can react instantaneously, and there must always be some residual difference between the synchronized or slaved time scale and the standard to which it is synchronized. This residual difference is dependent upon the nature of the fluctuations being removed and the response characteristics of the control system.

All timing control systems are essentially nonlinear since the functions being controlled are periodic and the phase difference upon which synchronization control depends must likewise be cyclic. However, in most cases the allowable error is small with respect to a phase period; and the immediate transient behavior of most control systems can be analyzed on a linear basis, although the initial settling characteristic and pull-out limits may have to be determined by phase/plane analysis or other more or less sophisticated nonlinear mathematical approaches.

C. CHARACTERISTICS OF SYNCHRONIZATION CONTROL SYSTEMS

A comprehensive survey of all possible time-synchronization control systems is beyond the scope of this report. However, certain dominant types will be examined briefly in order to outline the capabilities and restrictions of these devices.

1. Discontinuous Control Systems

a. Quasi-Periodic Resetting of Phase. The most elementary type of discontinuous synchronization control is that of resetting the phase whenever the error reaches an assigned limit, φ_m. The resulting phase-error characteristic is more or less a periodic sawtooth in form with an amplitude equal to the maximum allowable error - which may be plus or minus, depending upon the sense of the drift.

If observation of the time scale is independent of the resetting, all possible values of the error are equally likely and the probability density, $P(\varphi)$, of the error is as follows for three different conditions:

$$P(\varphi) = 0 \text{ when } \varphi < \varphi_m$$

$$P(\varphi) = 1/\varphi_m \text{ when } 0 < \varphi < \varphi_m$$

$$P(\varphi) = 0 \text{ when } \varphi > \varphi_m$$

The mean value of the error is then

$$\bar{\varphi} = \varphi_m/2$$

and the rms deviation from the mean is

$$\sigma = \varphi_m/2\pi\sqrt{3}$$

b. Periodic Resetting of Timing Rate and Phase. Maintaining synchronism by simply removing the error whenever it reaches a maximum tolerable amount leaves a mean residual error equal to one half the tolerance. However, a better control is obtained if, in addition to removing the phase error, a proportional correction is made to the timing rate as well.

Consider a time scale function whose rate of change of phase (or frequency offset with respect to some standard with which it is being synchronized) is $\omega(t)$ and which has a constant frequency drift, $\dot{\omega}$. At intervals t_1 apart, the phase difference is reset to zero and the frequency is changed by an amount proportional to the phase reset.

The frequency (offset with respect to the standard) during the n^{th} interval between resets is represented by $\omega_n(t)$ and can be expressed as

$$\omega_n(t) = \omega(n) + \dot{\omega}t$$

The phase is reset to zero at the start of the interval so that the phase runoff during the interval is

$$\varphi(n) = \omega(n)\, t_1 + \dot{\omega}t_1^{\,2}/2$$

The frequency at the start of the $(n+1)^{th}$ interval is equal to the frequency at the end of the preceding interval less an amount proportional to the phase runoff, namely,

$$\omega(n + 1) = \omega_n(t_1) - K\,\varphi(n)$$

Solving the expression for $\varphi(n)$ and for $\omega(n)$, and substituting gives an expression for the frequency at the beginning of the subsequent interval such that

$$\omega(n+1) = \frac{\varphi(n)}{t_1}(1 - Kt_1) + \dot{\omega}t_1^2$$

The phase is again reset to zero at the beginning of the subsequent interval, thereby developing a phase runoff that can be expressed as

$$\varphi(n+1) = \omega(n+1)\,t_1 + \frac{\dot{\omega}t_1^2}{2}$$

Substituting the expression for $\omega(n+1)$ and rearranging the following "difference equation":

$$\varphi(n+1) - \varphi(n)\,(1 - Kt_1) = \dot{\omega}t_1^2$$

which gives the phase runoff in any interval in terms of the phase runoff in the preceding interval; the frequency drift, $\dot{\omega}$; and the control ratio, K.

This is a difference equation which can be solved by recourse to Z transforms or jump functions (ref. 138). In terms of jump functions, the LaPlace transform of a function passing through the successive points of peak runoff at the end of each interval is obtained from the difference equation in the form

$$e^s\,(Y(s) - \varphi(0)P(s)) - (1 - Kt_1)\,Y(s) = \dot{\omega}t_1^2\,\frac{e^s\,P(s)}{e^s - 1}$$

where Y(s) is the LaPlace transform of a function passing through the values of $\varphi(n)$ at the successive reset epochs; $\varphi(0)$ is the initial value of $\varphi(t)$; P(s) is the transform of a "unit pulse" defined by having unity value between n equals zero and n equals 1, and is zero elsewhere; and s is the complex transformation variable of the LaPlace transform.

Solving the foregoing expression for Y(s) yields

$$Y(s) = \varphi(0)\,\frac{e^s\,P(s)}{e^s - (1-Kt_1)} + \frac{e^s\,P(s)}{[\,e^s - (1-Kt_1)\,(e^s - 1)\,]}\,\dot{\omega}t_1^2$$

The inverse transform of this expression, as found in a table of jump function transforms (ref. 138), is then

$$\varphi(n) = \varphi(0)\,(1 - Kt_1)^n + \dot{\omega} t_1^2 \, \frac{1 - (1 - Kt_1)^n}{Kt_1}$$

Now, n is the index of the n^{th} interval of length t_1. Hence, n equals t/t_1

The quantity $1 - Kt_1$ is the fractional change of frequency per period. Let this quantity be represented by an exponential such that

$$1 - Kt_1 = e^{-at_1}$$

which, if Kt_1 is small, is very nearly e^{-Kt_1}.

Hence,

$$\varphi(t/t_1) = \varphi(0)\, e^{-Kt} + \frac{\dot{\omega} t_1}{K}(1 - e^{-Kt})$$

From this analysis it is apparent that where the phase is periodically reset to zero and the frequency is corrected in proportion to the error, any initial phase offset decays exponentially to zero and there is established a residual offset equal to the frequency change during a period divided by the control ratio.

A random offset in phase occurring in any reset interval is removed by reset at the end of the interval; but this removal causes the introduction of a change in the timing rate that produces a runoff in the next interval K times as large in the opposite direction, and which then decays exponentially as e^{-Kt}. If the factor K is small, the aggregate of these offset responses reflected in the rate corrections would be small and the fluctuations caused by random effects are not significantly affected by the rate corrections.

2. Continuous Control Systems

If the phase of a time-scale is stable enough for the change in phase with respect to a standard between one period and the next to be at most incremental, the relative phase (even though observed at discrete intervals) can be treated as a continuous variable and the operation of such a time synchronizing system can be characterized by differential equations rather than difference equations.

As previously discussed, a continuous time-synchronizing system (figure 51) consists basically of the time-scale function to be synchronized, a standard time scale to which it is slaved, some device for determining the phase of the scale relative to the standard, and a controller adapted to adjust the phase in accordance with the phase error.

The particular embodiment of each element of such a configuration varies widely from system to system, depending upon the application and the particular techniques by which the time scale is established. The implementation of these techniques ranges from the use of purely mechanical devices (as, for example, a mechanical coupling whereby the swing of one pendulum is synchronized with that of another) to highly-sophisticated, electro-mechanical or electronic systems employed to synchronize the complex of time code generators of missile tracking and telemetering systems.

In the electronic art the time-scale generator may be an oscillator or "clock-pulse generator" driving a frequency divider or counter. The count of this device - which is presented either as a digital readout (by waveforms of related frequencies presented on parallel leads or by pulses of different amplitudes and shapes) presented serially on a single lead - provides a "time code" identifying the epoch.

The phase of the time code relative to some external standard may be controlled either by adjusting the frequency of the master oscillator itself, by adjusting a phase shifter between the master oscillator and the counter, or by distorting the output waveform of the master oscillator so that the counter loses or gains counts.

The phase controller consists of circuitry adapted to produce the required phase adjustments (e.g., a motor turning an electromechanical phase shifter, a trigger circuit adding or blocking clock pulses at a counter input, a bias applied to some frequency-controlling element of the clock pulse generator, etc). It does so in response to some combination of integral, proportional, differential, or other function of the phase difference between the local time scale and the reference to which it is being synchronized.

The phase difference detector is a device that accepts both the time scale being synchronized and the standard as inputs and produces some measure of the relative phase as output. Again, the precise form of the phase difference detector depends upon the nature of the time scales and upon the particular circuit techniques being used. For example, a sampler and analog-to-digital converter are employed in the domain of computer techniques and a phase detector and filter are used in analog techniques, etc.

The most common form of phase difference detector - or "phase discriminator" as it is sometimes called - is basically a "cross correlating" device which determines a more or less exact representation of the average of the instantaneous product of the local and standard time scale waveforms. This relationship can be expressed as

$$\Psi_{12}(x) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} S_1(t)\, S_2(t+x)\, dt$$

Theoretically, cross correlation involves integration over all time; but where the functions are periodic with commensurate periods and if random effects are ignored, the correlation over a single period is equal to the correlation over all time. The response of the correlator is given by the expression

$$\psi(\varphi_1, \varphi) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} S_1(\omega t + \varphi_1)\, S(\omega t + \varphi)\, d(\omega t)$$

where S_1 is the standard time scale function (having phase φ_1 with respect to some arbitrary absolute reference), S is the local time scale having phase φ with respect to the same arbitrary absolute reference, ω is the frequency in radians per unit time, and both S_1 and S are periodic over any 2π radians of their arguments.

By substituting $\omega t - \varphi$ for ωt and noting that with periodic functions of the same period the same correlation is obtained over any period of 2π, the correlation function becomes

$$\psi(\varphi_1 - \varphi) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} S_1(\omega t + \varphi_1 - \varphi)\, S(\omega t)\, d(\omega t)$$

i.e., the correlation is directly a function of the phase difference between local and standard time scales.

a. Types of Correlation Functions. The local time scale may be represented by sharp "sampling" or "clock" pulses recurring at the period of the time scale. The correlation function would then be given by

$$\psi(\varphi_1 - \varphi) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} S_1(\omega t + \varphi_1 - \varphi)\, p(\omega t)\, d(\omega t)$$

where $p(\omega t)$ is an impulse function having a finite amplitude when t equals zero and is zero elsewhere, and with an integral value P that is finite, such that

$$P = \frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\omega t)\, d(\omega t)$$

The integrand of the correlation function then has a value other than zero only when ωt equals zero. Hence, the standard time scale function, as a function of the phase difference $(\varphi_1 - \varphi)$, can be taken out from under the integral to give the expression

$$\psi(\varphi_1 - \varphi) = S_1(\varphi_1 - \varphi)\frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\omega t)\, dt = P\, S_1(\varphi_1 - \varphi)$$

That is, where the correlation is a sampling of the standard time scale at the epochs of the local time scale, the correlation function is simply the shape of the standard time function as a function of the phase difference multiplied by the local pulse amplitude that has been averaged over a period.

If then the standard time-scale function is a sinusoid

$$S_1 (\omega t + \varphi_1) = \sin (\omega t + \varphi_1)$$

the correlation function can be expressed simply as

$$\psi(\varphi_1 - \varphi) = P \sin (\varphi_1 - \varphi)$$

However, if the standard time-scale function is a sequence of pulses of arbitrary shape, the correlation function is simply the same shape as a function of the phase difference.

If the local time scale is a sinusoid and the standard time scale is a co-sinusoid of the same period, the correlation would be given by the relationship

$$\psi(\varphi_1 - \varphi) = \frac{1}{2\pi} \int_{-\pi}^{+\pi} \sin (\omega t + \varphi_1 - \varphi) \cos (\omega t)\, d(\omega t) = (1/2) \sin (\varphi_1 - \varphi)$$

b. General System Control Function. In general terms, the system control function is given by

$$\varphi = F (\varphi_1 - \varphi)$$

where the function symbol, F, signifies the action of the phase controller on the phase of the local time scale in response to the correlation between the local and standard time scales.

Control function F may have biases, thresholds, limits, hystereses, static friction, and/or other variable parameters or it may be otherwise nonlinear. An exact analysis for all the many possible control functions is much beyond the scope of this study.

Some information about the behavior of a time synchronizing system in the presence of noise and other small-signal disturbances can be established by making a small-signal linear approximation in which the correlation function is represented by a linear approximation and the control function is restricted to being a linear function in which superposition is valid.

c. Linearization of the System Function. For small deviations of the local time scale away from the standard, the correlation function can be expanded in a MacLaurin Series to yield the expression

$$\psi(\varphi_1 - \varphi) = \psi(0) + \psi'(0)(\varphi_1 - \varphi) + \text{(Terms of Higher Order)}$$

and if the higher-order terms are dropped, the system function becomes

$$\varphi(t) = F\ \psi'(0)\left[\frac{\psi(0)}{\psi'(0)} + \varphi_1 - \varphi\right]$$

Absorb correlation function derivative $\psi'(0)$ into the system function and let the ratio $\psi(0)/\psi'(0)$ be equal to φ_o.[8] Then if the control function F is linear so that superposition holds, the system function can be written as

$$\varphi(t) = \frac{F}{1+F}\varphi_1(t) + \frac{F}{1+F}\varphi_o$$

d. Synchronization Error Function. In time synchronization the principal quantity of interest is the phase error of the local time scale - i.e., the amount by which the local time scale differs from the standard - rather than the absolute phase of the local time scale itself which is assumed to be a more or less smooth linear function of time, except for the phase error.

Letting the phase error be $\Delta\varphi$, the error function is given by

$$\Delta\varphi = \varphi_1 - \varphi = \varphi_1 - \frac{F}{1+F}\varphi_1 - \frac{F}{1+F}\varphi_o$$

which reduces immediately to

$$\Delta\varphi = \frac{1}{1+F}\varphi_1 - \frac{F}{1+F}\varphi_o$$

e. Continuous Linear Control Systems

(1) Proportional Control

The simplest control function is one that makes the phase shift response of the local time scale directly proportional to the phase difference between the local and the standard time scales. The control function is then given by the relationship

- - - - - - -

[8]The expression for φ_o can be written as $\psi(0) = \psi'(0)\ \varphi$; i.e., φ is the negative of that value of the error $\varphi_1 - \varphi$ which makes the correlation zero.

$$\varphi(t) = \frac{A}{1 + A} \varphi_1(t) + \frac{A}{1 + A} \varphi_o$$

and the error function is expressed as

$$\Delta\varphi(t) = \frac{1}{1 + A} \varphi_1(t) + \frac{A}{1 + A} \varphi_o$$

With this type of control it appears that (to the extent that the control ratio is large) the local time scale will be an exact replica of the standard plus a fixed offset amounting to the bias of the correlator.

However, if the standard time scale is contaminated by noise or any other disturbance, this would also be repeated exactly. Furthermore, if the local time scale (when uncontrolled) differs even slightly in frequency from the standard, an error builds up at a rate proportional to the difference in frequency divided by the control ratio - a quantity that increases without limit as time increases and one which would practically carry the correlator beyond its linear range, and cause the synchronizing control to unlock and slip counts.

Therefore, this type of control is not used. All synchronizing systems basically control the rate of change of phase, or of frequency, as discussed in the balance of this appendix.

(2) Frequency Control

A commonly-used control function adjusts the rate of change of phase or frequency offset proportional to the phase difference between the local time scale and the standard, thereby giving a control function of the form

$$\dot{\varphi} = A(\varphi_o + \varphi_1 - \varphi)$$

In terms of the LaPlace transform, this becomes

$$s\varphi(s) = \varphi(0) = A(\varphi_o/s + \varphi_1(s) - \varphi(s))$$

or

$$\varphi(s) = \frac{A}{(s + A)} \varphi_1(s) + \frac{\varphi(0)}{(s + A)} + \frac{A\varphi_o}{s(s + A)}$$

where $\varphi(0)$ is the initial phase of the local time scale and φ_0 is the correlator bias. The corresponding time function then takes the form

$$\varphi(t) = A\,e^{-At} * \varphi_1(t) + \varphi(0)\,e^{-At} + \varphi_0\,(1 - e^{-At})$$

where (*) signifies the convolution of $\varphi_1(t)$ with e^{-At}.

If $\varphi_1(t)$ is a constant $\varphi_1(0)$, then the convolution term becomes

$$\varphi(t) = \varphi_1(0)\,(1 - e^{-At}) \text{ (+ Other Terms as in Preceding Equations)}$$

If $\varphi_1(t)$ has a frequency offset, $\dot{\varphi}_1$, then

$$\varphi(t) = \dot{\varphi}_1 t - \frac{\dot{\varphi}}{A}(1 - e^{-At}) \text{ (+ Same Terms Added to Preceding Equation)}$$

Thus if the phase of the standard is fixed with respect to the common absolute scale, the local time scale simply subsides to the same phase as e^{-At} plus an offset due to the correlator bias.

If the phase of the standard has a constant rate of change, then the local time scale settles to the same rate of change with a phase offset equal to the rate of change of phase divided by the control ratio.

If $\varphi_1(t)$ has some random component (due to contamination by noise, for example), the time synchronizer would respond as a low pass filter. Thus, the perturbations of $\varphi_1(t)$ can be expressed as a Fourier integral in the form

$$\varphi_1(f) = \int_{-\infty}^{+\infty} \varphi_1(t)\,e^{-j2\pi ft}\,dt$$

and the response - discarding the other terms, and including the initial value and the correlator bias - would be

$$\varphi(f) = \frac{1}{(1 + j2\pi f/A)}\,\varphi_1(f)$$

Such a filter cuts off at 6 db per octave at a breakpoint when f is equal to $A/2\pi$ cycles per unit time.

Thus, if there is no significant difference in frequency (as would be the case where the local and standard time scales are highly stable), the control ratio, A, may be made very small so that the filter cuts off at a very low frequency, thereby discriminating sharply against noise and other random disturbances.

However, if there is any appreciable frequency drift or frequency difference, control ratio A must be large enough to keep the "lag", $\dot{\varphi}_1/A$, below the tolerable limit. However, increasing A widens the filter bandwidth, and hence allows more of the random fluctuations to pass and disturb the local time scale.

(3) Integral Frequency Control

A narrow-band discrimination against noise and other high frequency effects, with elimination of lag error, can be obtained by controlling the rate of change of phase of the local time scale proportional to the integral of the phase difference. With this type of control used under conditions of persistent error, an increasing change in the frequency will occur until the error disappears. The control function is then expressed by the relationship

$$\dot{\varphi} = K^2 \int_0^t (\varphi_o + \varphi_1(t) - \varphi(t)) \, dt$$

Taking derivatives of both sides, this reduces to

$$\ddot{\varphi} = K^2 (\varphi_o + \varphi_1 - \varphi)$$

The preceding equation is, however, the equation for harmonic motion; i.e., making the frequency proportional to the integral of the error alone produces an unstable system. To obtain stability, the change in frequency must be proportional to the sum of the error and its integral, viz.,

$$\dot{\varphi} = A(\varphi_o + \varphi_1 - \varphi) + K^2 \int_0^t (\varphi_o + \varphi_1 - \varphi) \, dt$$

Again taking derivatives, the preceding equation becomes

$$\ddot{\varphi} = A (\dot{\varphi}_1 - \dot{\varphi}) + K^2 (\varphi_o + \varphi_1 + \varphi)$$

whose LaPlace transform is

$$s^2 \varphi(s) - S \varphi(0) - \dot{\varphi}(0) = A s \varphi_1(s) - A \varphi_1(0) - A s \varphi(s) + A \varphi(0)$$
$$+ K^2 \varphi_o/s + K^2 \varphi_1(s) - K^2 \varphi(s)$$

It is convenient to let A be equal to $K^2/2$ so that the system will be critically damped; whereupon, the preceding expression reduces to

$$\varphi(s) = \left(1 - \frac{s^2}{(s+K)^2}\right)\varphi_1(s) - \frac{2K}{(s+K)^2}\varphi_1(0) + \frac{s+2K}{(s+K)^2}\varphi(0)$$

$$+ - \frac{1}{(s+K)^2}\dot{\varphi}(0) + \frac{K^2}{s(s+K)^2}\varphi_o$$

In the foregoing expression, all of the terms on the right, except for the first and the last, have no poles at the origin or in the right-half plane and hence they subside to zero as some function of e^{-Kt}. The last term subsides to the constant, φ_o, representing the correlator bias.

The term containing $\varphi_1(s)$ can be written as

$$\varphi_1(s) - \frac{s^2}{(s+K)^2}\quad\varphi_1(s)$$

The second term of the foregoing expression has no poles at the origin or in the right-half plane, even when $\varphi_1(t)$ is equal to $\dot{\varphi}t$. Hence, this system subsides to

$$\varphi(t) = \varphi_1(t) + \varphi_o$$

for variations of $\varphi_1(t)$ up to a constant offset in frequency.

Again, if $\varphi_1(t)$ has a random component caused by noise or other disturbance, the system will act as a low pass filter eliminating high frequency components of the disturbance. In this case, however, the filter cuts off at 12 db instead of 6 db per octave and since the synchronizing system will track a frequency offset with no error, the system bandwidth can be chosen to minimize the noise or other random perturbations, rather than to minimize the rate error.

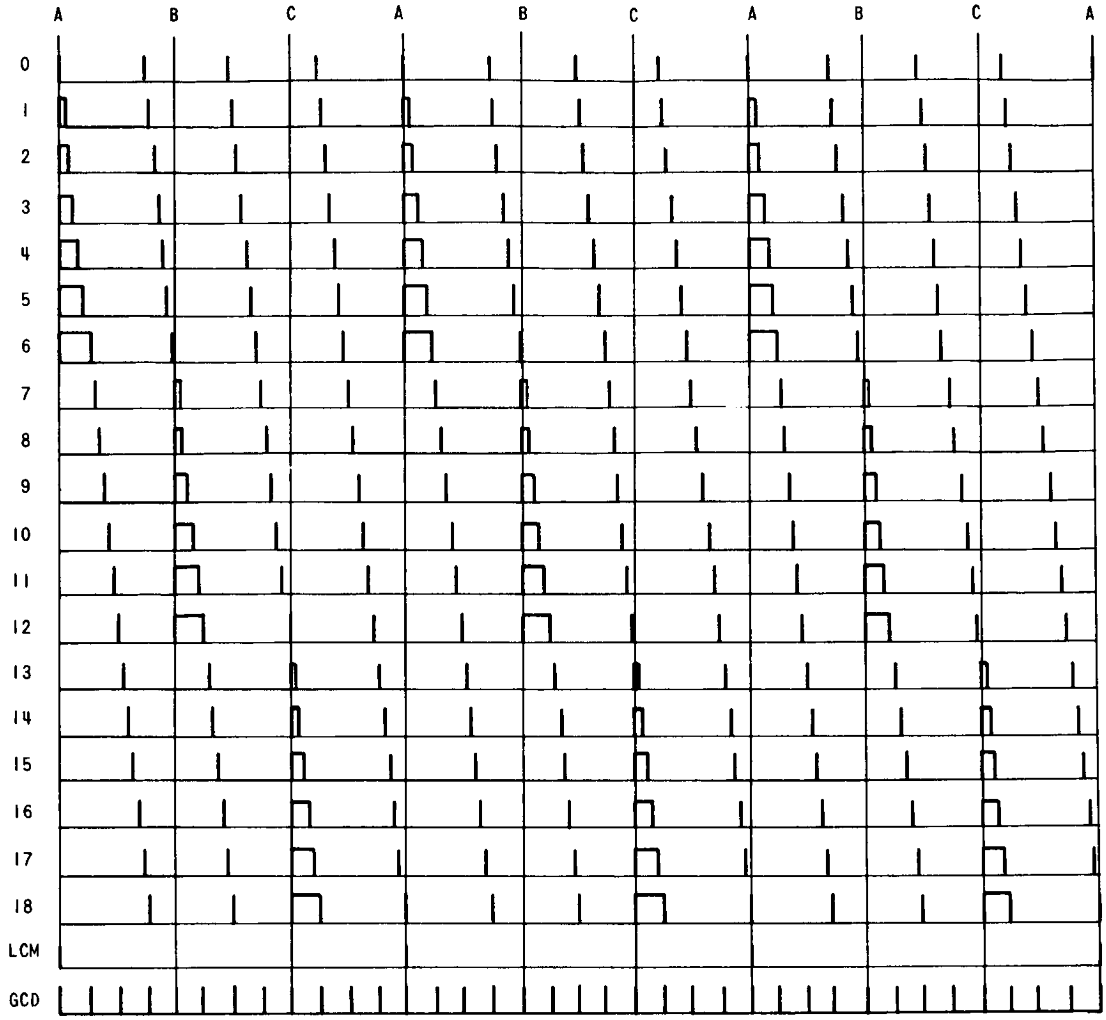


FIGURE 50. RELATIVE PHASE OF COMMENSURATE PERIODS

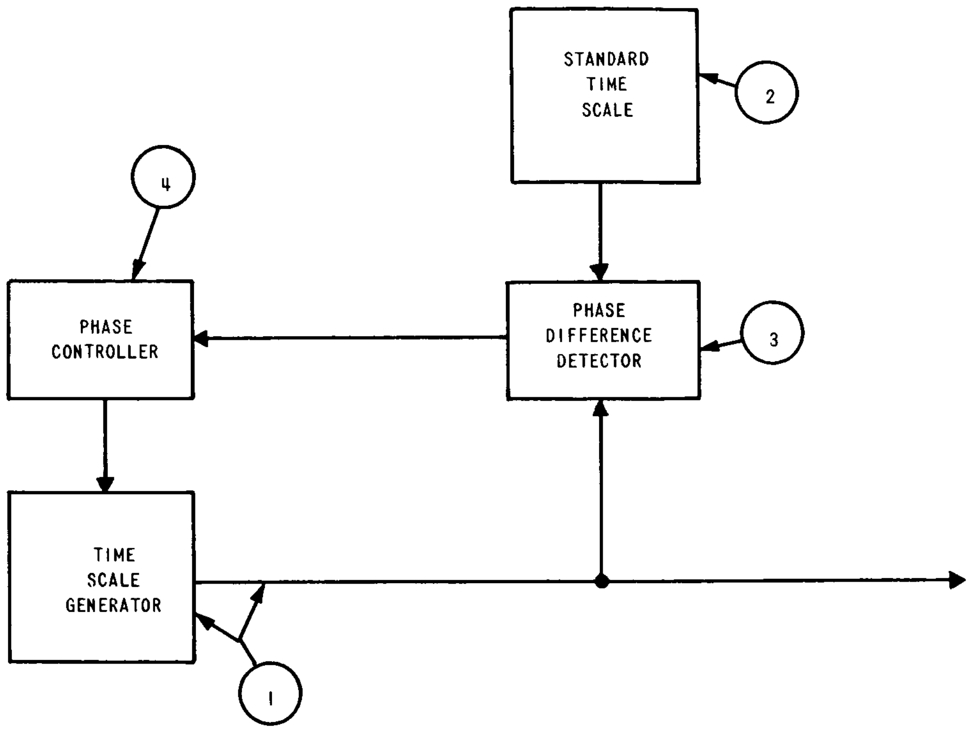


FIGURE 51. TIME SYNCHRONIZING SYSTEM, SIMPLIFIED BLOCK DIAGRAM

APPENDIX II

OMEGA TIMING RECEIVER DESIGN

A. INTRODUCTION

This appendix describes the design details of a receiver that automatically derives time synchronization information from a set of OMEGA signals. Although no such receiver has ever been built, the presentation which follows is intended to demonstrate the practicality of such a receiver to operate in the OMEGA environment.

B. AUTOMATIC SEQUENCE PHASE CONTROL

A system that will maintain more or less automatic alignment with the multiplex sequence is shown in the block diagram of figure 52. This system, which is called the automatic multiplex sequence correlator, consists of

- Three signal amplifiers (with linear detectors) each tuned to one of the three respective OMEGA signal channels
- A "diversity combiner" adapted to combine the responses in the three channels so as to generate the best possible representation of the signal envelope waveforms
- A frequency standard (or "timer") and frequency divider, providing "clocking pulses" at a rate of 10 per second.

The timer operates a "correlating function generator", which is a specialized counter circuit that produces the four waveform sequences shown in figure 53. These waveform sequences will now be described separately.

Waveform N is a set of 0.2-second pedestals exactly matching the irregular spacing of the gaps between OMEGA transmissions (refer to paragraph D.3 of section V and figure 21). Each pedestal, when aligned with the signal envelope sequence, will occur in a gap between transmissions and will therefore bracket only noise, not signal. Hence, the use of the label "N" (noise) waveform.

Waveform (S + N) consists of pairs of 0.1-second pedestals bracketing the N-waveform pedestals in such a manner that, when exactly aligned with the signal envelope waveforms, each pedestal will lie just on the beginning or end of a transmission.

The (S + N) function is applied in order to gate the corresponding portion of the signal envelope waveform into a storage or averaging filter, while the (N) function gates a corresponding inverted portion of the signal envelope waveform into the same averaging filter. Thus, the response of the filter is the average of the difference of the correlation of the (S + N) and the (N) functions with the incoming signals.

If these two functions are in exact alignment with the gaps in the signal-envelope function, a maximum response is obtained from the (S + N) correlation and the (N) correlation response will be pure noise; i.e., it will average zero. Any displacement of the functions in phase from exact alignment with the signals as received reduces the (S + N) correlation since half of the pedestals will occur at least partially in the gaps between signals. Conversely, the displacement increases the (N) correlation since the N-pedestals then occur more or less on the leading or lagging edge of the signal segments, causing a sharp drop in the average response.

Because of the irregular spacing of the transmission gaps, only the correct alignment of 10-seconds will produce full response from all (S + N) pedestals and zero response from all N pedestals. Hence, while there are other relative phases which produce lesser maxima of correlation, the correct maximum is the largest by an appreciable factor - even with some of the signals missing from the sequence, as will occur when one or more of the stations is very distant.

Waveforms LEAD and LAG are identical with the N-waveform, except that the LEAD pedestals occur 0.1 second earlier, and the LAG pedestals occur 0.1 second later than the N-pedestals. When the N-pedestals are phased to occur exactly on the gaps between segments of the sequence, the LEAD pedestals will be approximately bisected by the trailing edges of each signal segment and the LAG pedestals will be bisected by the leading edges.

The difference between the two responses as a function of relative phase between the correlating function waveforms and the signal envelopes is a null at exact alignment, while a departure from exact phase alignment causes a positive or negative swing with a relatively steep slope. Since the gaps between signals are of the order of 0.2 second, the sensitivity of the null correlation provided by the LEAD and LAG waveforms is of the order of a few milliseconds or better.

1. Correlating Function Generator

A digital logic structure for generating the correlating waveforms of the preceding discussion is shown in figure 54. This multiplex correlation function generator consists of a number of flip flops (FF's) connected as a six-stage binary counter, an auxiliary three-stage counter, a diode logic matrix, and two control gates: x and $\not x$.

Flip flops a, b, c, d, e, and f comprise the six-stage counter, with the states of stages d, e, and f operating on the diode logic matrix. Flip flops p, q, and r form the auxiliary three-stage counter, also operating on the logic matrix.

The diode matrix combines switching waveforms to form the stages of the counters for producing an output (x) - with any of the following combinations - and (not x) for all other combinations. (Note $\not d$ denotes "not d", etc.)

$\not d \, \not e \, \not f \, p \, q \, \not r$	$\not d \, \not e \, f \, p \, \not q \, r$
$d \, \not e \, \not f \, \not p \, \not q \, r$	$d \, \not e \, f \, p \, q \, \not r$
$\not d \, e \, \not f \, p \, \not q \, r$	$\not d \, e \, f \, \not p \, q \, r$
$d \, e \, \not f \, \not p \, q \, r$	$d \, e \, f \, \not p \, \not q \, r$

The operation of the units is as follows: At any stage of operation flip flops d, e, and f must stand at some one (and only one) of the eight combinations of three binary digits representing the first three digits of the symbols for (x) in the foregoing tabulation. If flip flops p, q, and r are not standing on the value corresponding to the count in p, q, and r, the output of the diode matrix is $\not x$, so that the 0.1-clocking pulses operating the unit are then applied to the auxiliary counter (p, q, r). This counter, therefore, cycles through its count until it reaches the combination corresponding to the count standing in d, e, and f. When this count is reached, the output of the matrix changes from $\not x$ to x, thereby switching the clocking pulses to the six-stage register and causing it to cycle forward eight counts until it resets all three stages.

The reset of counter c causes counters d, e, and f to advance by one count and also resets counters p, q, and r. The output of the diode matrix changes back to $\not x$, which switches the clocking pulses back to counter p and the cycle repeats at the next combination of the logic table.

The p, q, r combinations providing the x outputs with each d, e, f combination are chosen so that the switching between $\not x$ a nd x takes place at counts corresponding to the OMEGA-length coding sequence.

The switching and correlating waveforms necessary to determine the phase match and to decommutate the OMEGA signals are then obtained by proper combinations of the counter waveforms - as shown in the timing diagram of figure 55.

2. Sequence Alignment Procedure

Alignment of the local multiplexing function with the signals, as received, is accomplished as follows:

The received signal waveforms are viewed in an oscilloscope (figure 52) on a 10-second linear sweep timed by the reset of counter (f) of the multiplex function generator. The phase of the sweep is adjusted by means of a timer "slewing control" so that the leading edge of one of the signal segments coincides with the start of the trace. After one or more 10-second sequence periods, the peak correlation response is observed for a maximum and the timer phase is readjusted to bring the next segment of the envelope waveform sequence to coincide with the start of the sweep. This procedure is repeated until all eight possible alignments have been tried.

One of the eight alignments will produce a maximum response from the "peak correlator." The timer phase is returned to that value and a fine adjustment is made to obtain a maximum response.

This step brings the alignment to within the control range of the "null-correlator," which then continuously corrects the timer phase so as to hold the correlating waveforms in alignment with the received signal envelopes.

Alternatively, the timer phase can be adjusted initially so that the start of a 10-second interval defined by the oscilloscope sweep occurs at an even 10 seconds of universal time; or the pattern of signal segment amplitudes can be analysed on the basis of which station will produce the largest signals at the given location, and the local timer phase then can be slewed so the largest response occupies the appropriate position on the oscilloscope trace.

Upon reaching the correct alignment, the "peak correlator" response [(S + N) - (N)] rises to a maximum positive value and the "null correlation" [(LAG) - (LEAD)] decreases to a null. Any deviation from exact alignment causes the null response to depart from the null and to adjust the timer phase so as to bring the null response back to zero.

3. Timing Accuracy of Sequence Correlation

The signal segment of each station is delayed by the time of transit from the station to the receiver. Since the distances are unequal, the observed signal segments will be shifted relative to one another by the differences in distance traversed. Hence, the gaps between segments, as observed at a receiver, vary from 0.16 second to 0.24 second.

The null correlator controlling the phase of the local-timer multiplex sequence approximates the averages of these shifts and then goes to zero at a relative phase corresponding to the average transmission time from the several observed stations to the point of observation. This procedure is weighted somewhat by the relative amplitudes of the signal segments, as observed.

At any given location - if close to one station - the next three stations that are closest will each be approximately 4000 to 6000 miles distant, and the signals of the most distant stations will be attenuated to such an extent as to be negligible. If the given location is more or less equidistant from the three or four nearer stations, the distance is not less than 3000 or 4000 miles - with perhaps one or two more-distant signals observable at distances of 6000 to 8000 miles.

Considering the system to be governed by the five nearest stations, the average distance is probably never more than 4000 miles, and not less than 3000 miles.

Hence, the phase retardation due to transmission time - regardless of the location of the receiver - will be in the order of 0.015 second, with an uncertainty of approximately 0.005 second.

4. Phase Measurement

The multiplex sequence correlating function examined in the preceding discussion aligns the 30-second timing epochs produced by the receiver time to within approximately ± 5 milliseconds (± 5000 microseconds) of the corresponding epochs of the received signals. This alignment can be refined by observing the phase of the various rf and modulation signal components of the local timer with respect to the corresponding components of the received signals from one or more stations. A mechanism for accomplishing this measurement on the signals from one station is shown in figure 56, the block diagram of the signal phase indicator. Subsequent paragraphs give more-detailed expositions of the component blocks and their operation.

Referring to figure 56, a highly-stable local timer is seen to operate a Reference Generator which generates a set of cw reference waves, one component at each of the characteristic OMEGA frequencies (13.6, 11-1/3, and 10.2 kHz; and 3400, 1133-1/3, 226-2/3, 45-1/2, and 11-1/3 Hz), and a series of 0.1-second clocking pulses.

The clocking pulses operate a multiplex (MPX) correlating waveform generator (as previously described), and the combination of cw reference generator and MPX waveform generator are interconnected in such a manner that the standard OMEGA relative phase condition is maintained; i.e., interconnected so that all sinusoidal component amplitudes pass through zero with the positive slope in coincidence with the start of every third multiplex sequence.

An "envelope waveform receiver" (consisting of three fixed tuned receivers of moderate stability) and a "diversity combiner" pick up the composite OMEGA signals from all stations within range in the three OMEGA rf channels, and develop a "best" signal envelope waveform.

The envelope waveform is correlated with the multiplex correlating waveforms to provide information for achieving rough alignment (within ± 5 milliseconds) between the local reference waves and the signals as received, and also to provide multiplex switching functions to segregate the various signal components for further processing.

A "ganged phase shifter" unit derives a set of phase adjustable OMEGA reference waves from the reference generator output. These reference waves maintain the standard OMEGA relative phase pattern, but are adjustable in phase with respect to the local timer.

The signals of a particular station - as segregated by the multiplex function - are amplified and converted by a set of three "tracking filters" into continuous waves of exactly the same phase. These waves are then compared in phase with the corresponding shifted reference waves in a set of phase detectors or "phase correlators." The phase difference indications or phase "errors" obtained thereby are combined in an "ambiguity resolving relay cascade" and then applied to a servo adjusting the setting of the ganged phase shifter in order to bring all phase errors to a null - from whence the setting of the phase shifter corresponds to the amount the unshifted local references lead or lag the signals of the particular station, as received.

The total phase shift required to accomplish this match in phase between the shifted references and the received signals is then indicated in terms of periods of the 10.2-kHz component.

5. Phase Control Function

If it is desired that the timer shall hold the phase of the OMEGA signals as it occurs at the receiver, the phase error indication can be applied to control the timer frequency directly in order to adjust the phase of the local references in such a manner that the phase differences tend to zero. However, the signals are retarded in phase by the time of their transmission (as much as 30 milliseconds) from the transmitters. Furthermore, the propagation suffers a systematic diurnal variation (which can amount to more than 200 microseconds under some conditions) in addition to fairly persistent short-term fluctuations of up to several microseconds. Since timing standards are now available with frequency stabilities in the order of several parts in 10^{12} or better, a much more stable synchronization can be realized if the phase difference indications are first corrected for calculated propagation delays and diurnal variations, and then integrated to determine the average deviation from the mean of all signals that can be observed. The timer frequency is then corrected manually from time to time so as to minimize the offset from the mean.

6. Circuit Function Details

A detailed functional description of the various phase-measuring circuit components will now be given.

a. Timer

The timer should be a precision frequency standard from which the characteristic OMEGA common multiple frequency (204 kHz) can be derived. This unit must also have sufficient stability to maintain its phase with respect to the mean phase of the OMEGA system within the desired tolerance of ± 1 microsecond for at least several hours, and preferably for 24 hours. Since this tolerance implies a stability in the order of $1:10^{11}$, the timer should be an atomic standard of good quality - although a good crystal standard ($1:10^9$) would serve with somewhat less timing stability.

b. Reference and Multiplex (MPX) Waveform Generator

The timer operates the reference generator (figure 57). This assembly - which consists of flip flops, gates, and diode logic networks, etc. - is a frequency reference synthesizer that operates as follows:

The 204-kHz timing wave from the timer is first divided by two, and then by nine and ten in parallel to produce the 11-1/3 and 102-kHz reference waves. The 204-kHz timing wave also operates a divide-by-15 counter to produce the 13.6-kHz component.

Coincidence between the 13.6- and 10.2-kHz outputs produces a 3.4-kHz component, which is then divided by 17 to give 200 Hz, and then by 20 to give 10 Hz in order to provide the 1/10-second clocking pulses for the MPX generator.

Coincidence between the 10.2- and 11-1/3-kHz components produces an 1133-1/3 Hz wave which is divided by five to produce the 226-2/3 Hz component, by five again to produce the 45-1/3 Hz component, and by four to produce the 11-1/3 Hz component.

The 11-1/3 Hz component is then divided by 34 to provide the 30-second epoch timing markers.

Because of the common division by two in the 11-1/3 and 10.2-kHz channels for which there is no counterpart in the 13.6-kHz channel, the 13.6-kHz wave possesses a phase reversal ambiguity (depending upon how the counters happen to start up) which, if in the wrong phase, prevents the 13.6-kHz wave from ever being coincident with the other two and thus violating the fundamental OMEGA format specification.

This ambiguity is eliminated by applying the 1133-Hz component (obtained by mixing the 10.2- and 11-1/3-kHz components) as a reset trigger to the divide-by-15 counter supplying the 13.6-kHz component. If the 13.6-kHz component has the wrong phase, the reset trigger causes it to jump a half cycle. If the phase is correct, the reset trigger has no effect since it then always occurs just after the divide-by-15 counter has reset anyway.

The 30-second epoch markers and the 10-second multiplex waveforms - though exactly commensurate, being derived from the same timing source - may have any relative phase in discrete steps of periods of 3.4 kHz. To assure correct alignment between the 11-1/3 Hz component and the MPX waveforms, the 30-second epoch markers are applied to reset the divide-by-17 and divide-by-20 counters, and the multiplex generator so that the start of every third multiplex sequence coincides with a 30-second timing epoch marker. Again, if the alignment is incorrect, the MPX waveforms are jumped to conform; if the alignment is correct, there is no reaction.

c. Tracking Filters

The essential elements of the tracking filters are shown in the block diagram of figure 58. These filters convert the discontinuous 1-second segments of a wave of particular frequency from one station into a continuous wave.

The circuit consists of a stable "voltage controlled" oscillator and a voltage variable attenuator (AGC amplifier with fractional gain) operating at the carrier frequency of the wave to be received.

The attenuated oscillator output is subtracted from the incoming signals at the antenna terminals (prior to the processing or narrow-band filtering of any other signal) in a simple linear subtraction circuit such as that of a hybrid transformer (not a modulator, mixer, phase detector, or any other type of nonlinear circuit). The phasor difference between the incoming signal and the attenuated locally-generated signal is amplified in a high gain amplifier-limiter and fed to two parallel phase detectors whose references are in quadrature - one coming directly from the stable oscillator and the other by way of a 90-degree phase bridge.

The output of the "quadrature" detector (reference in quadrature with the oscillator output) is integrated or averaged, and applied to control the rate of change-of-phase of the oscillator. The response of the in-phase detector is likewise integrated and applied to control the "voltage variable attenuator".

The action of this circuit is to adjust the phase and amplitude of the local signal so as to exactly cancel the received signal at the terminals of the antenna in order to reduce to null the outputs of both in-phase and quadrature detectors. To the extent that the amplifier gain is large the match of the local reference to the incoming signal is then independent of the phase and amplitude characteristics of the amplifier/limiter,[9] thereby eliminating from the phase indication any effect of amplifier instability or phase shift.

The action of each tracking filter is limited to the signals from one station by providing multiplex switching between each phase detector and its filter, between its oscillator and the reference input to the phase detector, and at the local signal input to the antenna circuit. When a signal is being received, the phase and amplitude of the local signal is controlled by the incoming signal. Between transmissions of that particular component from that station, the oscillator maintains both the frequency defined by the integrated error stored in the oscillator control integrator and the signal attenuation defined by the integrated error stored in the amplitude control integrator. Thus, when the signal returns in the next sequence, only a small - or even zero - difference must be adjusted.

At any one frequency only one signal component is received at a time so that the same input circuit and signal amplifier can serve for the signals from all stations in one frequency channel. However, the stable oscillator, the error integrators, and the AGC attenuator must store the phase and amplitude of a particular component when that component is not being received. A separate set of these components is required for each component to be measured.

d. Phase Demodulation

Since the error integrators acting on the output of the quadrature phase detector in the tracking filters greatly attenuate the phase modulation components, the local v-c oscillator phase does not follow the phase modulation swings of the incoming signals. Hence, the amplified phasor difference has a large quadrature component at the modulation frequency which is demodulated by the quadrature phase detector, thus eliminating the need for a separate phase demodulator.

- - - - - - -

[9] If the phasor difference is down only 20 db, for example, the phase of the local reference signal cannot differ from the received signal by more than 6 degrees of phase, or 1.3 microseconds at 10.2 kHz.

e. Ganged Phase Shifter

The ganged phase shifter assembly (figure 59) consists of a set of six phase shifters operating on the six sinusoidal frequency components of the OMEGA signal format (13.6, 11-1/3, and 10.2 kHz, and 226-2/3, 45-1/3 and 11-1/3 Hz). These phase shifters are geared together in the ratio of frequencies such that all six shifted components shift the same amount in time for a give rotation of the phase shifter unit input shaft, thereby maintaining the standard OMEGA phase alignment - although shiftable in phase.

The outputs of the 13.6- and 10.2-kHz phase shifters are mixed to produce a 3.4 kHz signal and the 11-1/3 kHz and 10.2-kHz signals are mixed to produce an 1133-Hz component - both of which likewise shift the same amount in time for a given rotation of the phase shifter.

f. Phase Correlator

The phase correlator (figure 59) - which consists of a set of eight phase detectors and a cascade relay unit for resolving phase ambiguity - functions as follows:

One phase detector compares the phase of the 11-1/3 Hz reference component from the ganged phase shifter with the 11-1/3 Hz modulation output from the 10.2-kHz tracking filter. The response of this phase detector, representing the phase difference between the shifted reference and the modulation component demodulated by the tracking filter, is applied to the first threshold unit of a "cascade relay unit."

The cascade relay unit (figure 60) is a set of relays, or equivalent, connected in a specific order such that a connection-through is seized by the unit with the lowest order in the set whose threshold is exceeded.

Two other phase detectors are provided to compare the phase of the 45-1/3 and 226-2/3 Hz components from the ganged phase shifter with the corresponding modulation components from the 11.2- and 13.6-kHz tracking filters. The resulting responses of the phase detectors are applied to the second and third stages of the cascade relay.

The cw carrier outputs of the 11-1/3 and 10.2-kHz tracking filters are mixed to provide a 1133-Hz component from the incoming signals. This component is compared in a fourth phase detector with the corresponding reference from the ganged phase shifter and the phase detector output is applied to the fourth stage of the relay cascade.

The cw carrier outputs of the 13.6- and 10.2-kHz tracking filters are mixed to provide a 3.4-kHz component from the incoming signals. This component is compared in a fifth phase detector with the corresponding 3.4-kHz reference from the ganged phase shifter and the phase error signal is applied to the fifth and last stage of the relay cascade.

g. Fine Phase Control

Fine control of the shifted reference phase is obtained by comparing the phase of the 13.6-, 11-1/3- and 10.2-kHz shifted references with the corresponding tracking filter outputs and summing the error signals. Thus when the cascade relays are fully satisfied, the control of the servo adjusting the ganged phase shifters is the sum of the phase errors at the three carrier frequencies.

h. Operation of Phase Correlator

When first turned on (or after a counter jump or other malfunction), the shifted references may have any phase with respect to the signal components. The lowest order phase detector having an output above the threshold seizes control of the phase control servo, thereby driving the phase shifters so as to bring that component to a null.

As soon as the threshold is reached, the corresponding cascaded relay drops out. This action shifts control of the servo to the next higher-frequency phase detector, which will then be over its threshold. This procedure continues, shifting control to each higher frequency in succession until all five cascade-relay thresholds are satisfied. Control is then shifted to the sum of the carrier phase errors.

i. Phase Indication

With the ratio of frequencies specified for the OMEGA signal format, one rotation of the 11-1/3-Hz phase shifter corresponds to 900 revolutions of the 10.2-kHz phase shifter, 1000 revolutions of the 11-1/3-Hz phase shifter, and 1200 revolutions of the 13.6-kHz phase shifter.

In accordance with OMEGA practice, the readout may be calibrated in units of "Centicycles" or cecs - i.e., 1 percent of one cycle of the 10.2-kHz frequency. The total unambiguous range of the ganged phase shifter is thus 900 cycles (of the 10.2-kHz period) or 90,000 cecs - i.e., approximately 0.09 second.

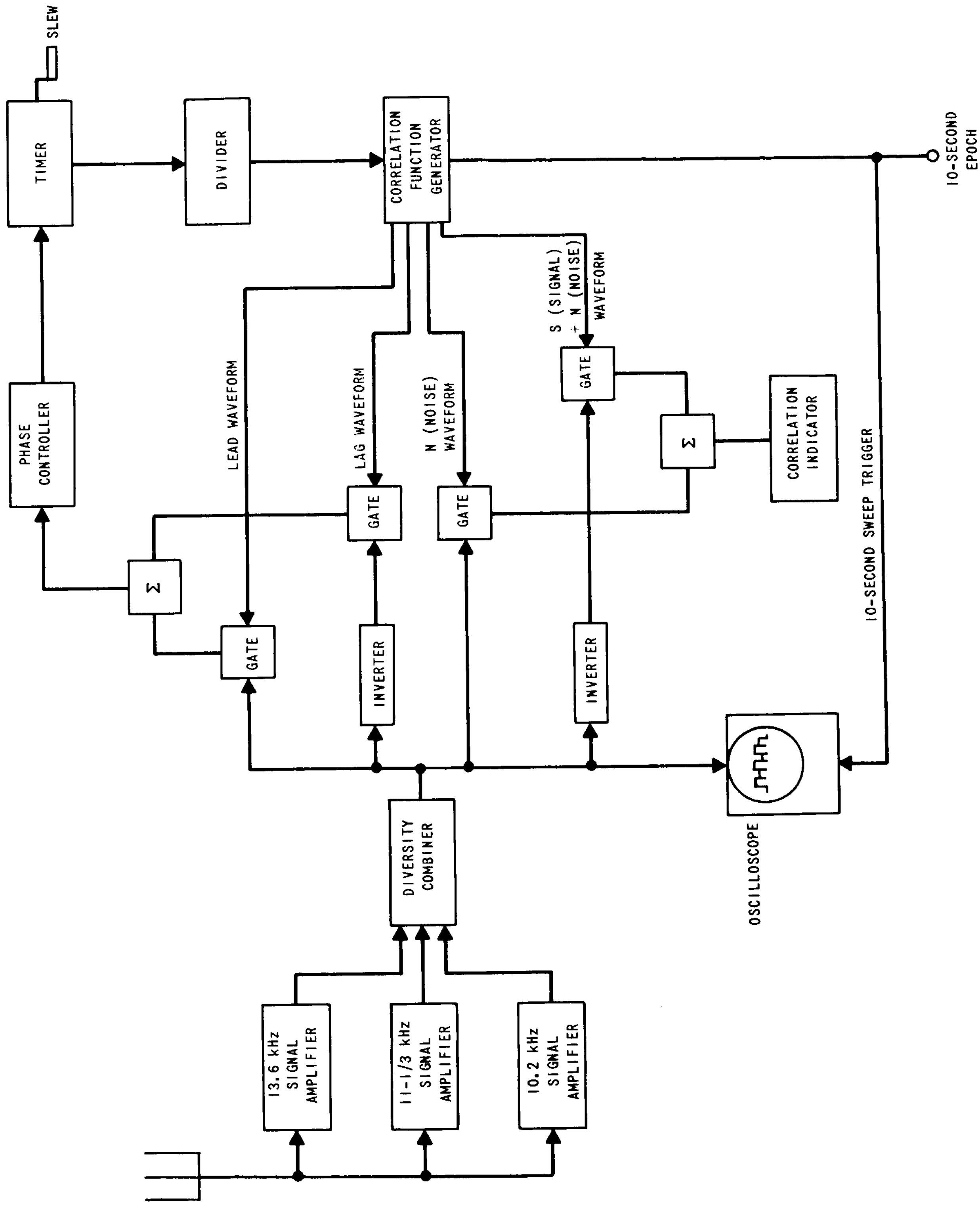


FIGURE 52. AUTOMATIC MULTIPLEX SEQUENCE CORRELATOR, BLOCK DIAGRAM

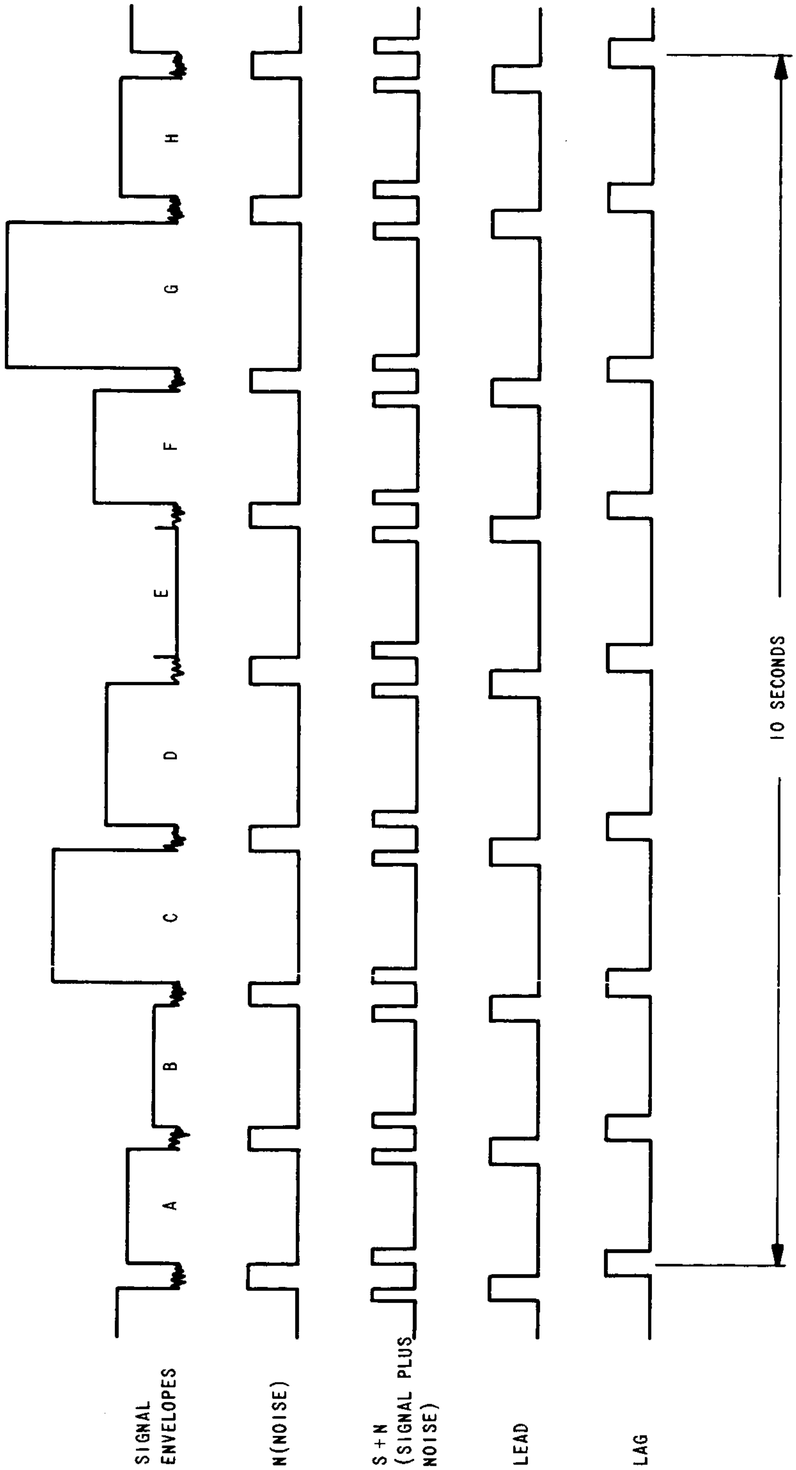
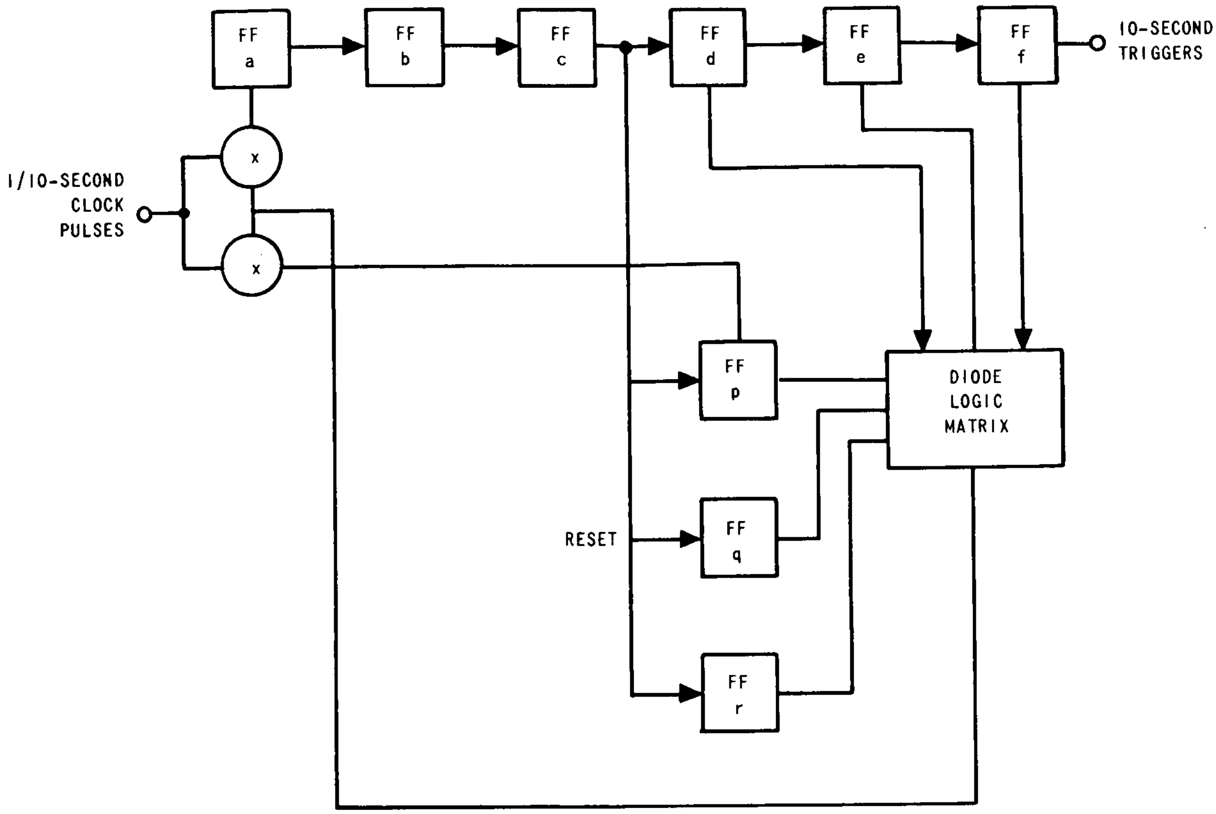


FIGURE 53. MULTIPLEX CORRELATING WAVEFORMS, TIMING DIAGRAM



$$
\begin{aligned}
x = {} & \bar{d}\,\bar{e}\,\bar{f}\;\; p\,q\,\bar{r} \\
& + d\,\bar{e}\,\bar{f}\;\; \bar{p}\,\bar{q}\,r \\
& + \bar{d}\,e\,\bar{f}\;\; p\,\bar{q}\,r \\
& + d\,e\,\bar{f}\;\; \bar{p}\,q\,r \\
& + \bar{d}\,\bar{e}\,f\;\; p\,\bar{q}\,r \\
& + d\,\bar{e}\,f\;\; p\,q\,\bar{r} \\
& + \bar{d}\,e\,f\;\; \bar{p}\,q\,r \\
& + d\,e\,f\;\; \bar{p}\,\bar{q}\,r
\end{aligned}
$$

FIGURE 54. MULTIPLEX CORRELATION FUNCTION GENERATOR, BLOCK DIAGRAM

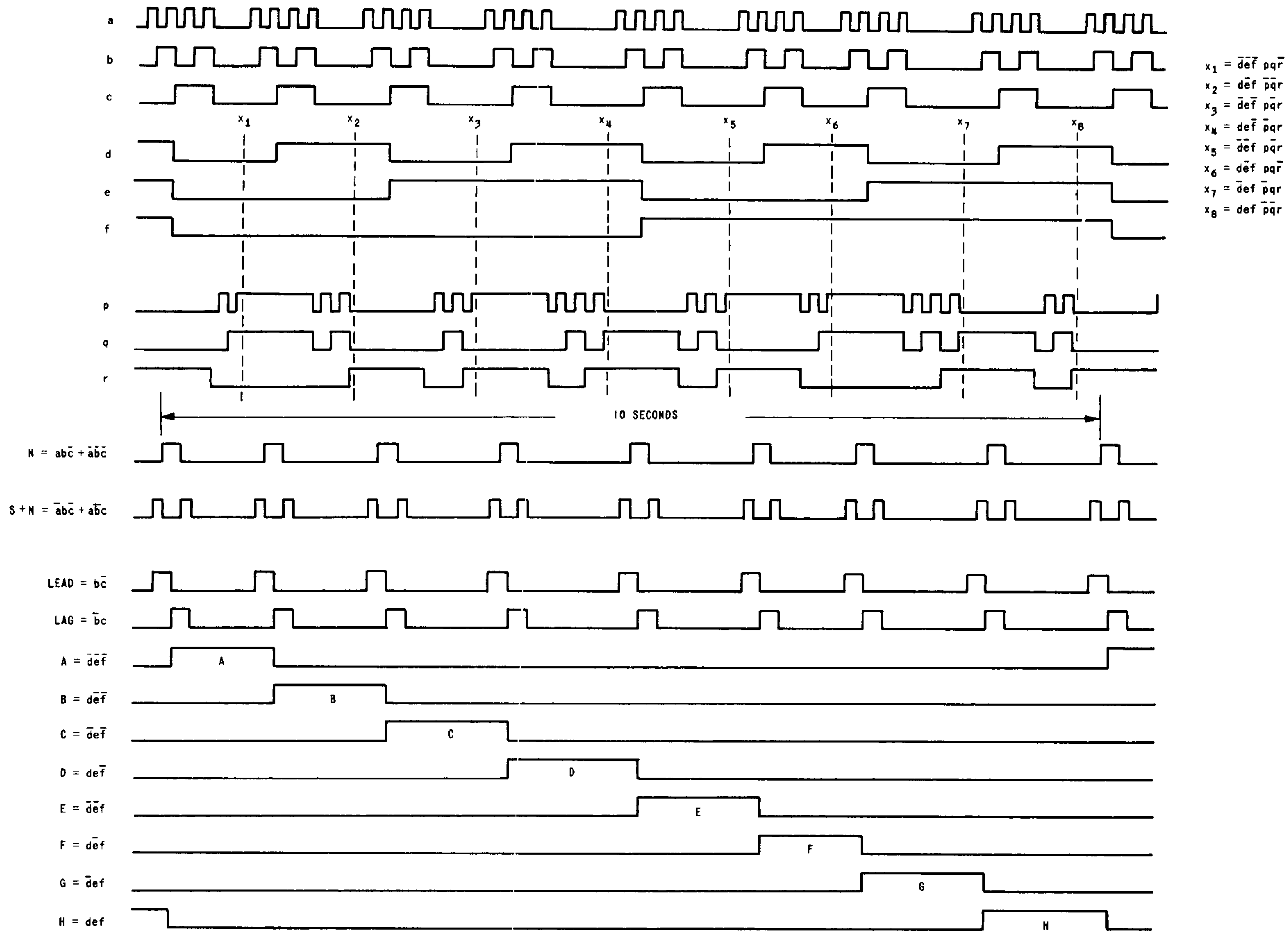


FIGURE 55. OMEGA MULTIPLEX WAVEFORMS, TIMING DIAGRAM

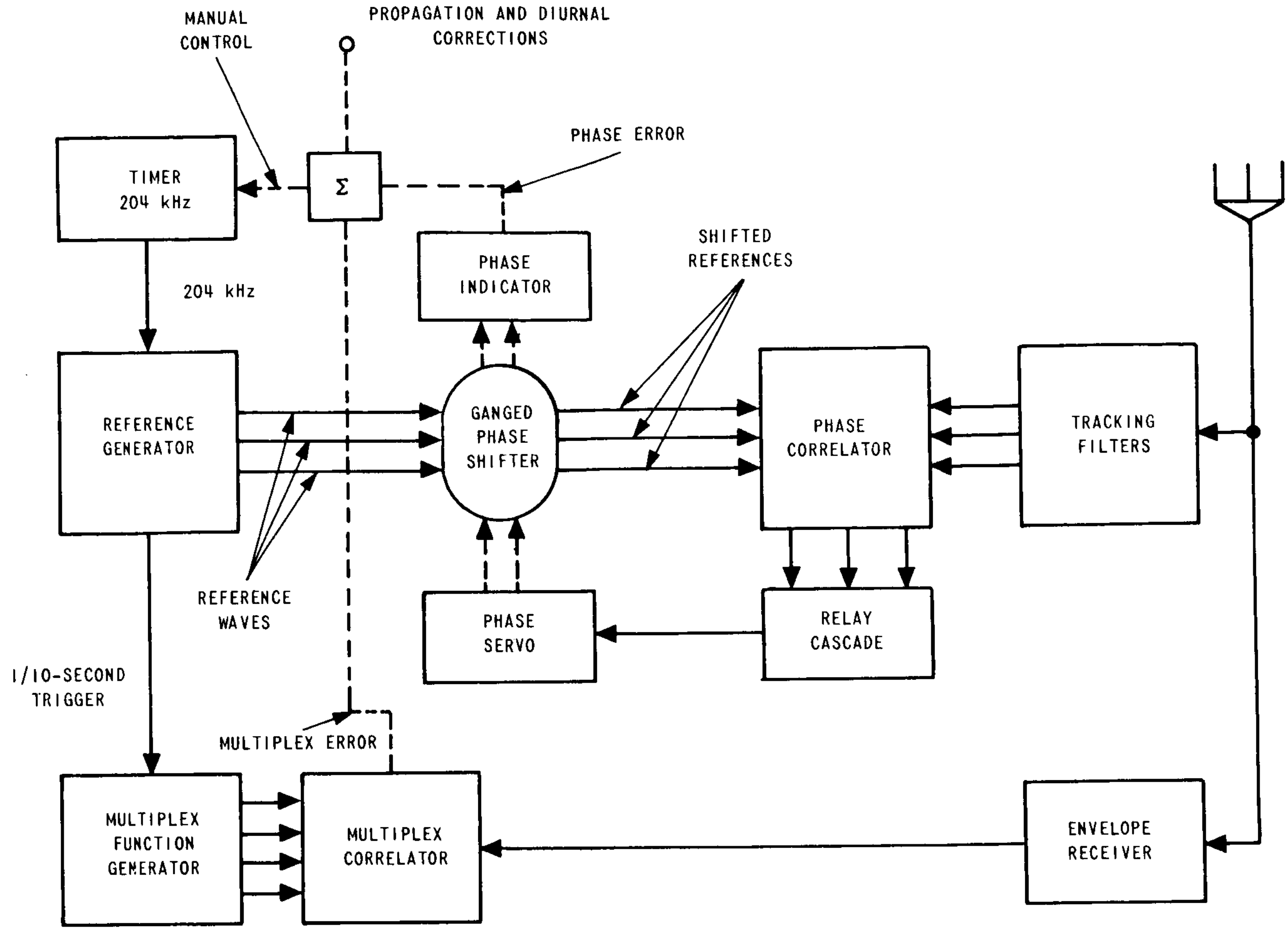


FIGURE 56. SIGNAL PHASE INDICATOR, BLOCK DIAGRAM

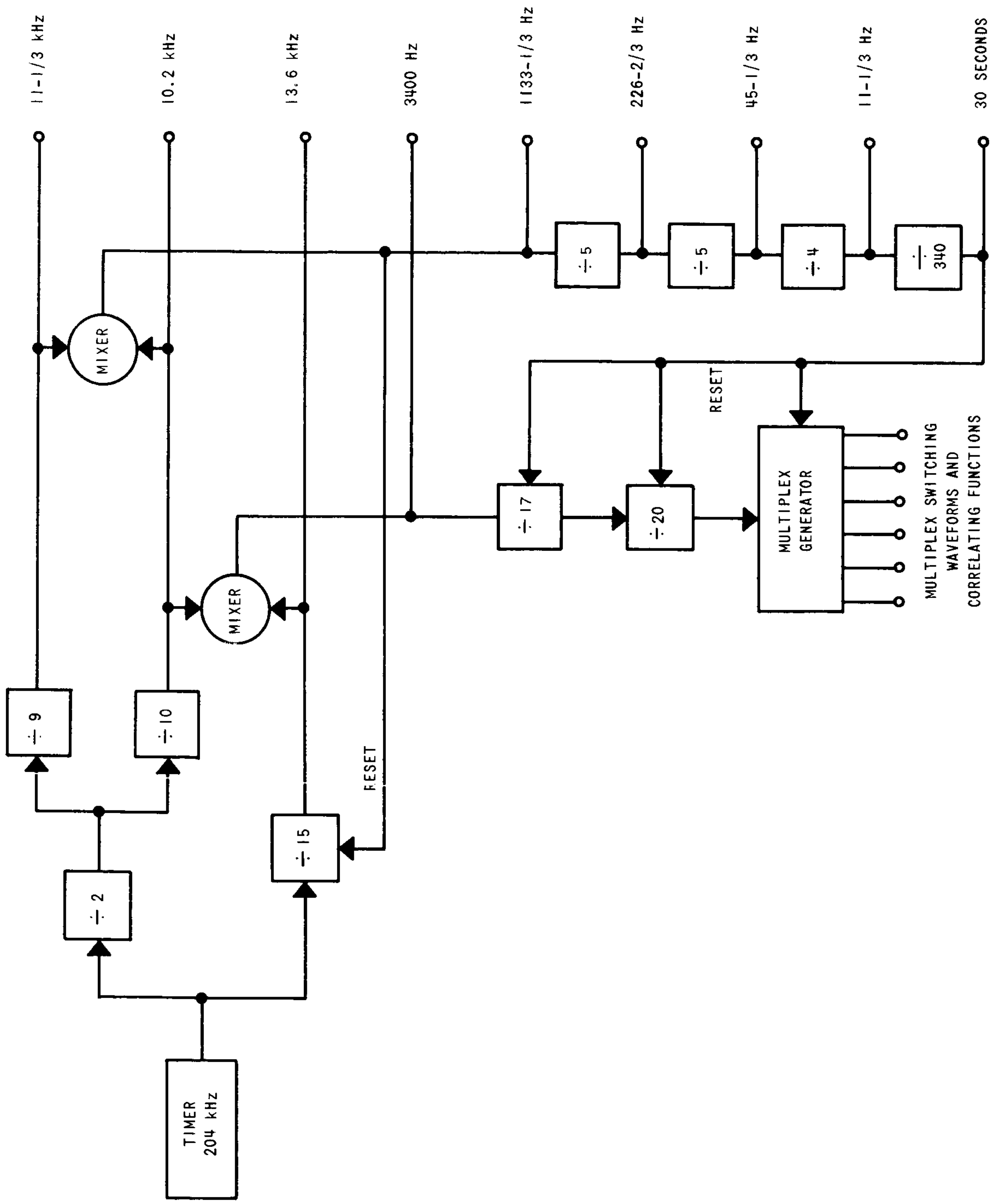


FIGURE 57. REFERENCE SYNTHESIZER, BLOCK DIAGRAM

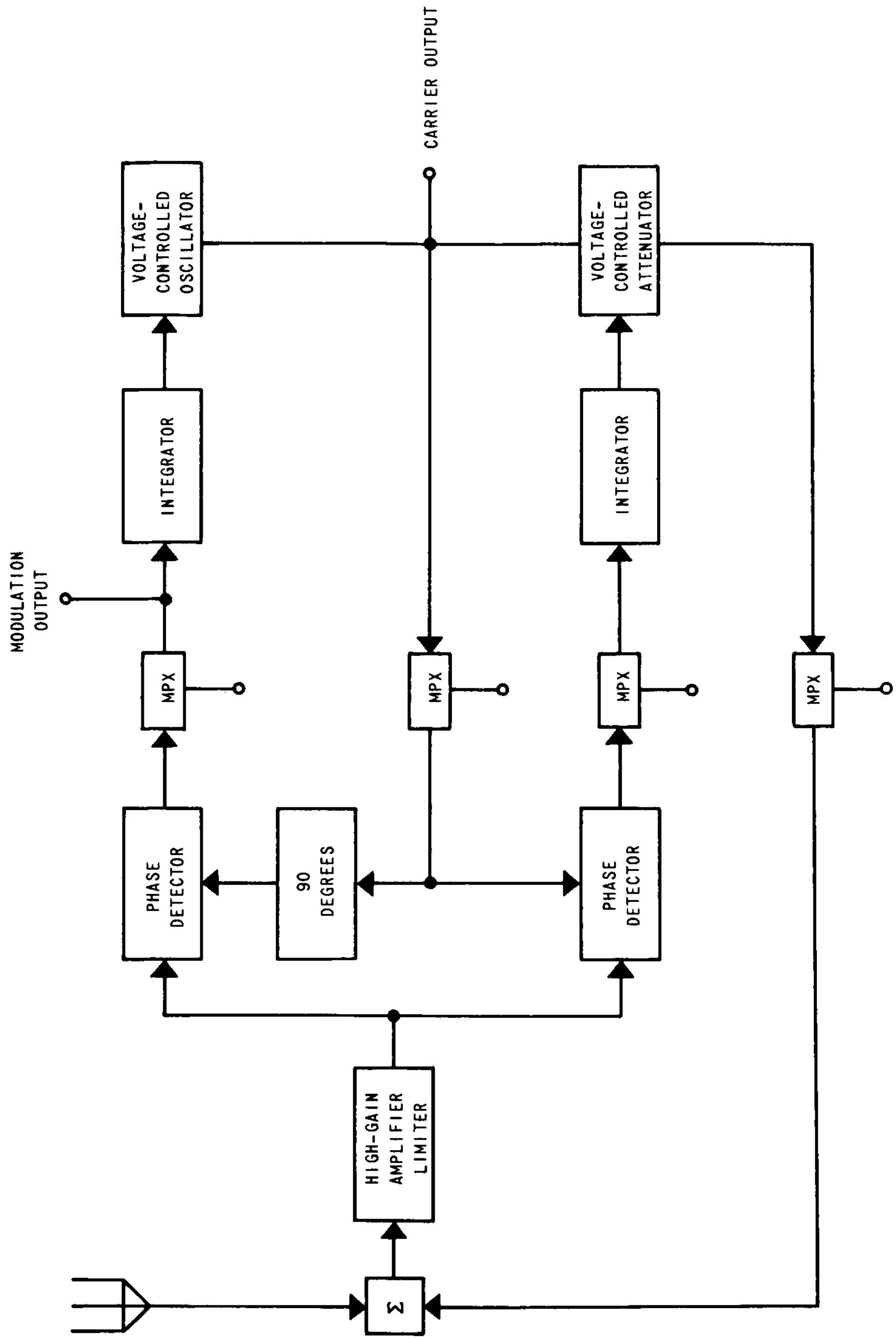


FIGURE 58. TRACKING FILTER, BLOCK DIAGRAM

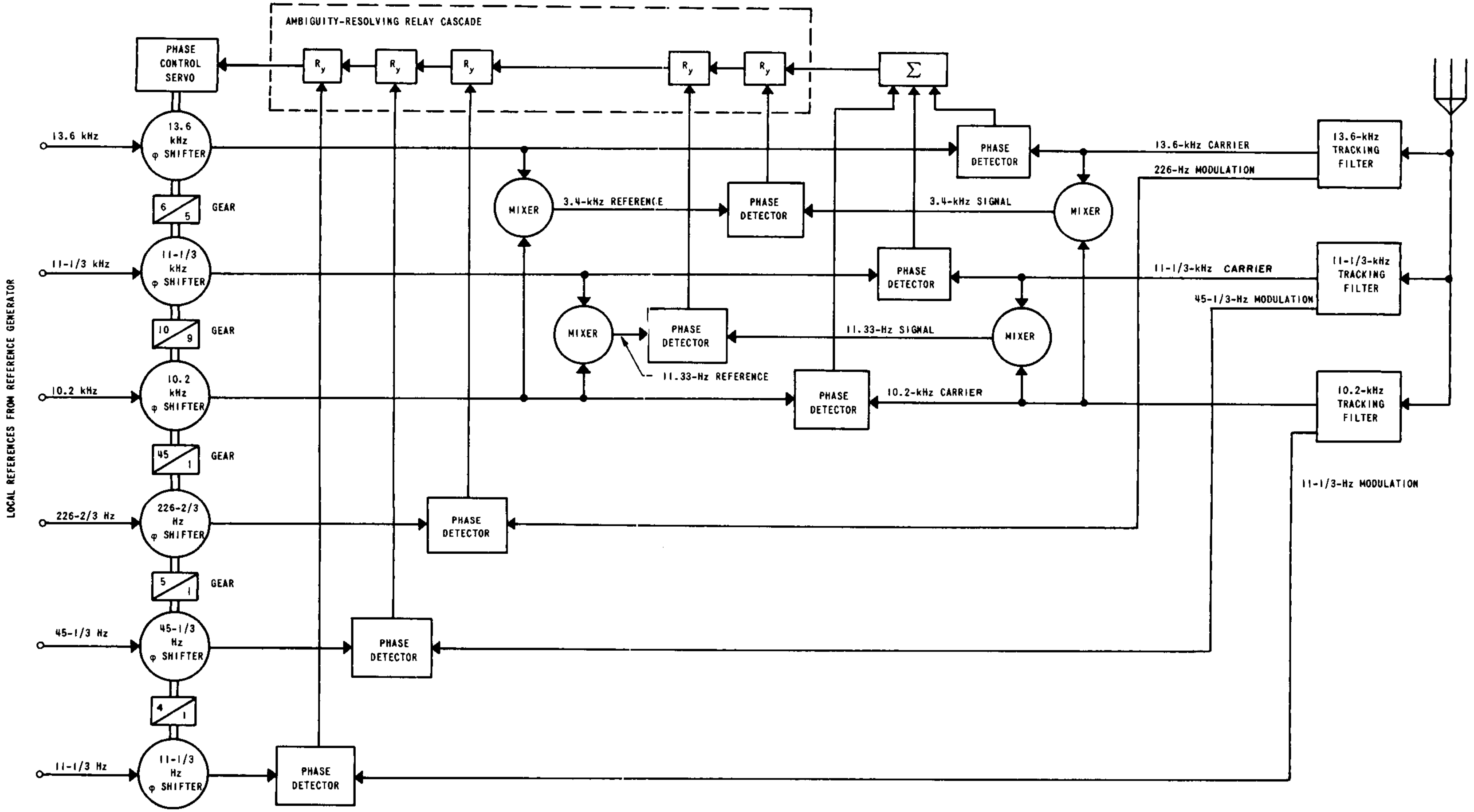


FIGURE 59. GANGED PHASE SHIFTER AND PHASE CORRELATOR, BLOCK DIAGRAM

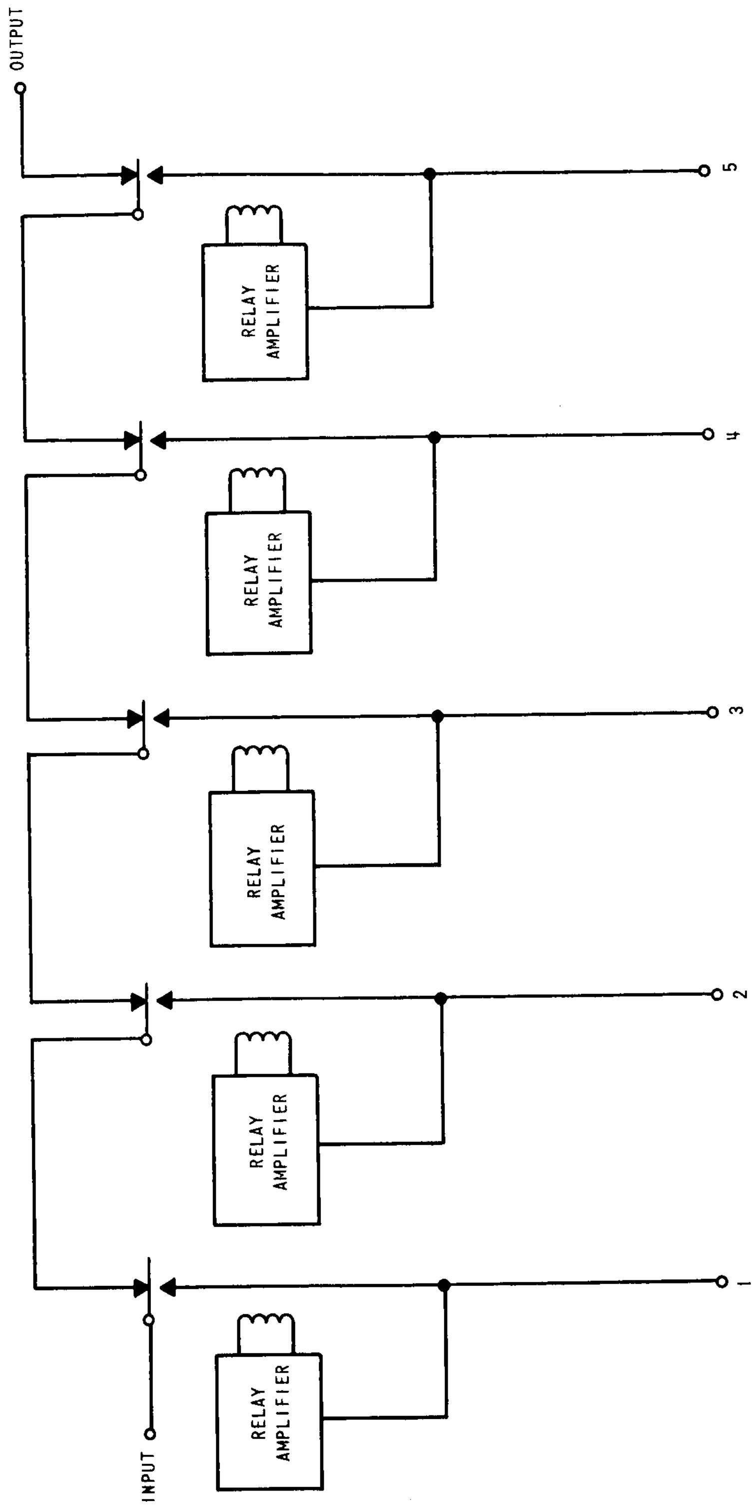


FIGURE 60. RELAY CASCADE UNIT, SIMPLIFIED SCHEMATIC DIAGRAM

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